DOE Hydrogen Program
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Hydrogen Delivery Infrastructure Options Analysis

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Project ID: PD11 Kelly

Overview

Timeline

- Start – June 2005
- Finish – July 2007
- 35 percent complete

Budget

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

Barriers

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

Targets

- 2006: Delivery infrastructure criteria
- 2010: <$1.70/gge delivery + dispensing
- 2015: <$1.00/gge delivery + dispensing

Partners

- TIAX
- GTI
- Air Liquide
- NREL & ANL
- Chevron
- Pinnacle West

Objectives

- Refine technical and cost data in H2A Component and Scenario Models to incorporate additional industrial input and evolving technology improvements
- Explore new options to reduce hydrogen delivery cost
- Expand H2A Component and Scenario Models to include new options
- Provide bases to recommend hydrogen delivery strategies

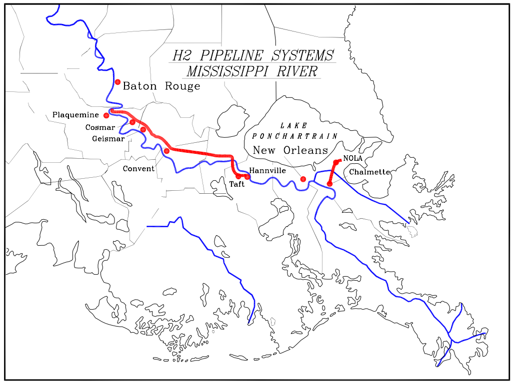
Approach

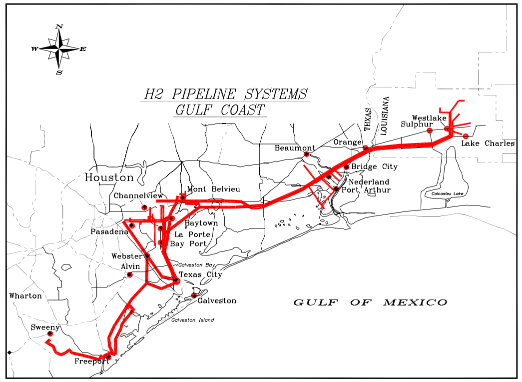
- Compile data on fossil and renewable energy resources, and on liquid and gas fuel distribution methods
- Develop energy requirements, capital costs, and operating costs for 19 hydrogen delivery methods
- Evaluate capability of existing infrastructure to deliver hydrogen
- Assess greenhouse gas and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

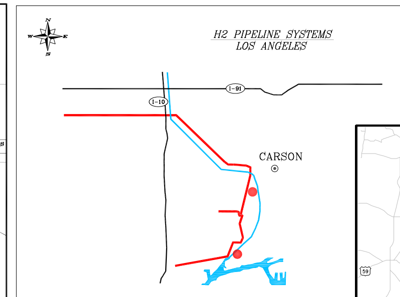
Delivery Options

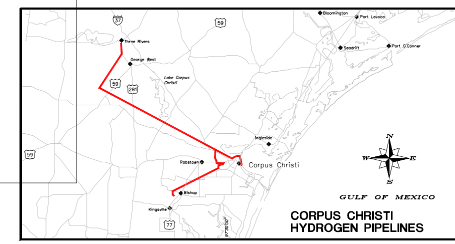
1: Dedicated pipelines for hydrogen gas delivery
2: Convert existing natural gas and oil pipelines to hydrogen gas delivery
3: Blend hydrogen with natural gas for pipeline transmission; separate at city gate
4: Truck or rail delivery of hydrogen gas
5: Truck or rail transport of hydrogen liquid
6: Novel hydrogen carriers
7: Methanol, ethanol, and ammonia as hydrogen carriers

Hydrogen Pipeline Experience



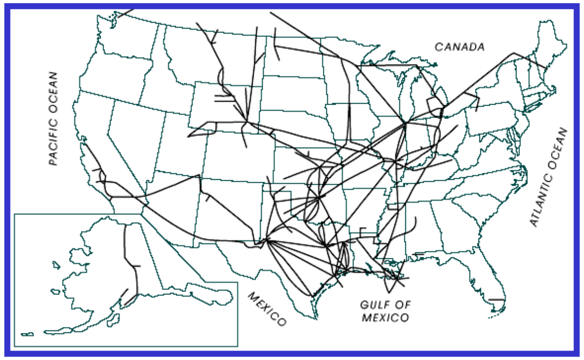


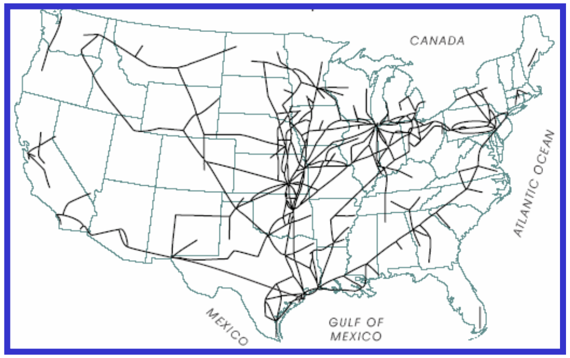


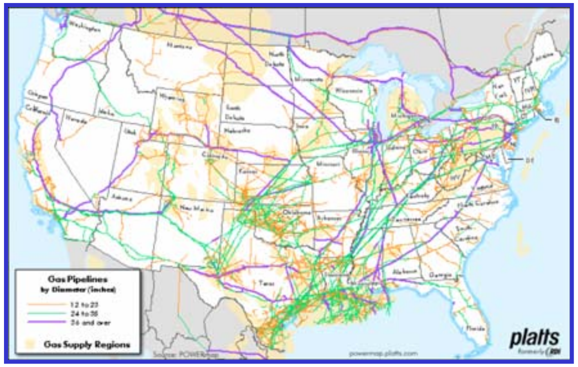


- **Transmission lines**
  - 600 miles in US
  - 10 in. to 18 in. lines (100,000-500,000 kg/d)
  - Sizes required for fully-developed hydrogen economy
  - \$0.5 to \$2 million per mile
  - ~ 2 to 5% more expensive than natural gas transmission lines
- **Compressors**
  - Reciprocating only
  - Compressor cost: 100% more than natural gas
- **Distribution lines**
  - None built to date
  - Borrow from natural gas experience
  - Very high cost; comparable to transmission lines

Pipelines Available for Conversion







Crude Oil Pipelines

- Lines to transport crude
  - Gulf area to Midwest refineries
  - California to Gulf Coast refineries
- Availability for conversion
  - Near term: lines from depleted oil field
  - Long term: all lines

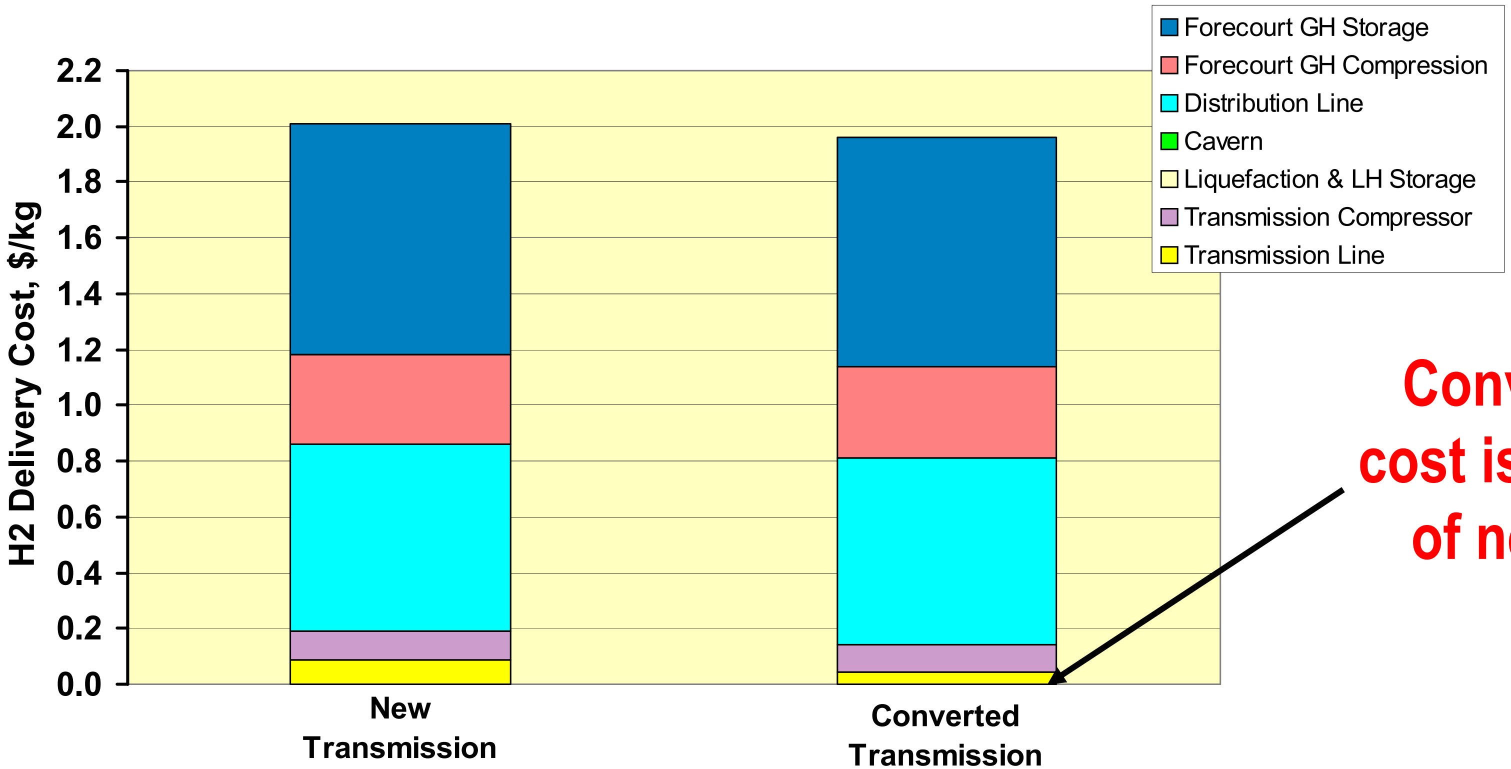
Petroleum Product Pipelines

- Lines to transport petroleum products
  - Gulf Coast refineries to Midwest
  - Gulf Coast refineries to East coast
- Availability for conversion
  - Near term: none
  - Long term: all lines

Natural Gas Pipelines

- Transmission lines available for conversion
  - Near term: none
  - Long term: all lines
- Distribution lines available for conversion
  - Plastic lines if H_2 pressure less than 100 psi

Economics for Converting Pipelines



Conversion cost is 1/3 cost of new line

- **474,000 kg/d hydrogen**
- **Transmission: 100 miles**
- **Forecourt: 320 stations**
- **Distribution line: 640 miles**

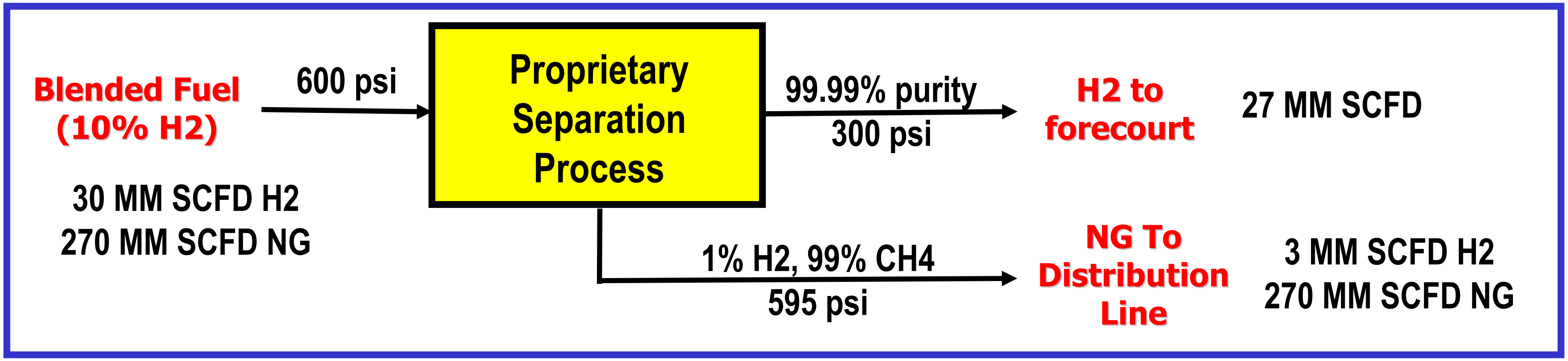
Modest savings as transmission line cost is small component of the total delivery cost

Natural Gas – Hydrogen Separation

Technology

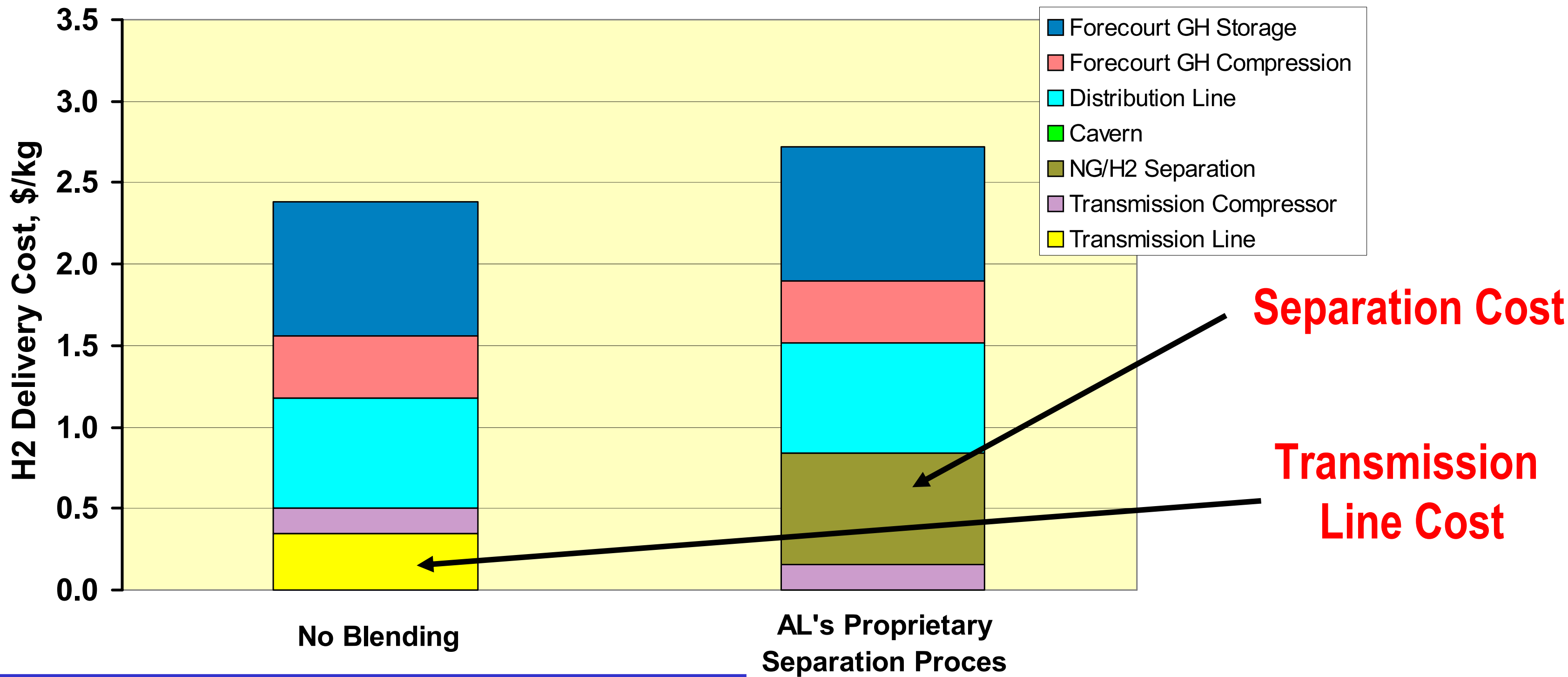
- Pressure Swing Absorption
- Membrane
- H_2 Absorber
- Methane Hydrate
- Proprietary Process

Air Liquide Proprietary Separation Process



- 99.99% hydrogen purity from mixtures with low hydrogen content
- Process based on mature technologies
- 90% hydrogen recovery
- 5 psi pressure loss for natural gas
- Natural gas odorant remains in natural gas stream
- Capital cost - $44 million; Power consumption - 11 MW; Annual O&M cost - $3.7 million

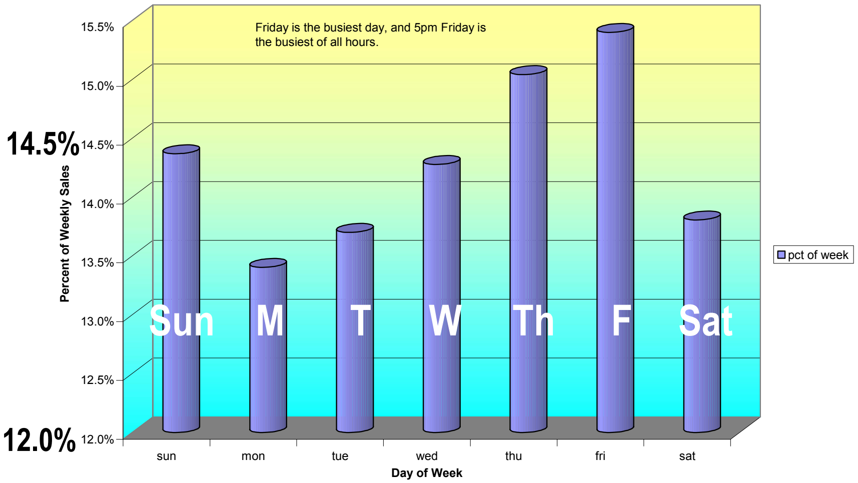
Economics of Separation

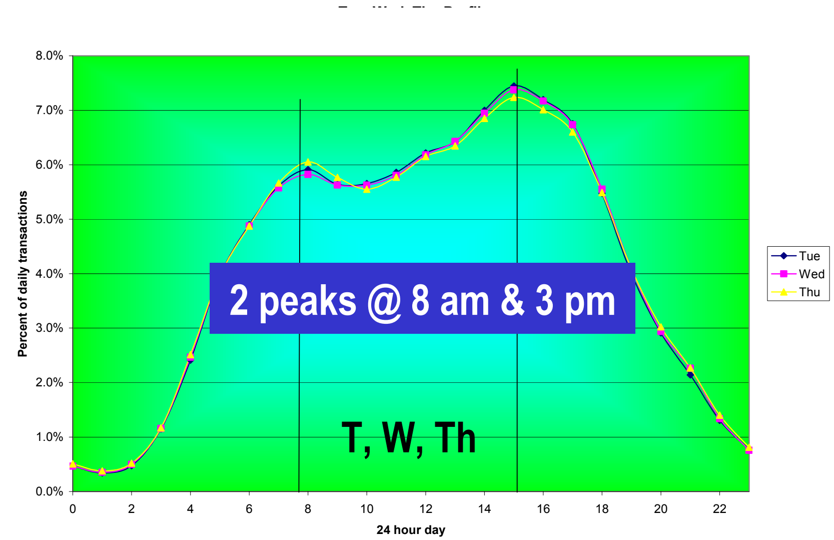


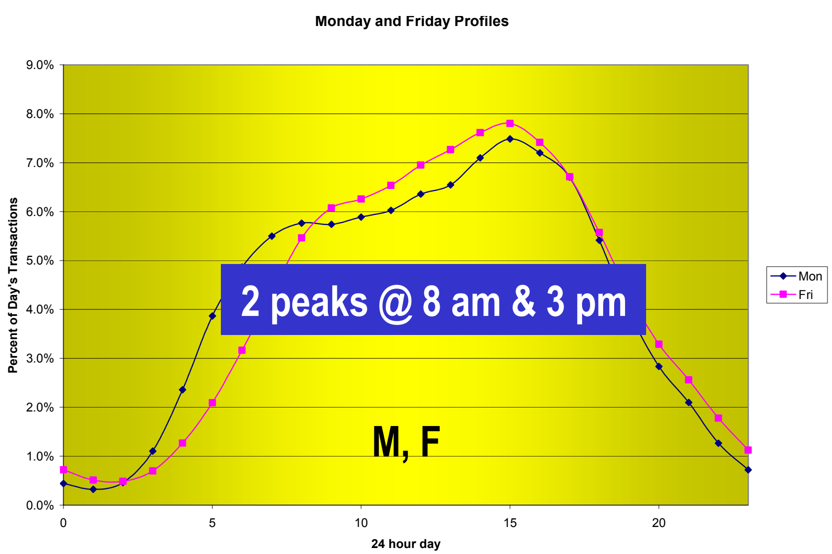
- H_2 demand: 64,000 kg/day
- Transmission: 100 miles
- Forecourt: 43 stations
- Distribution line: 86 miles

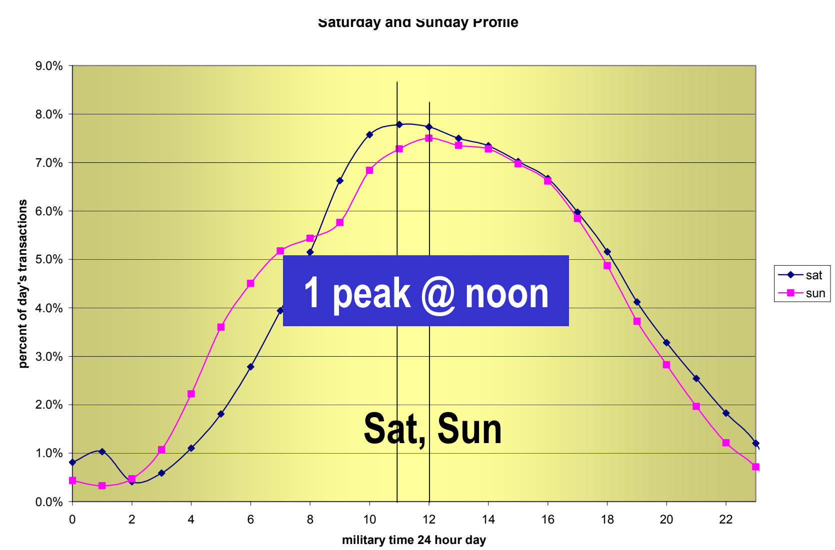
Cost effective only if production plant is more than 175 miles from city gate

Gas Station Fueling Profile

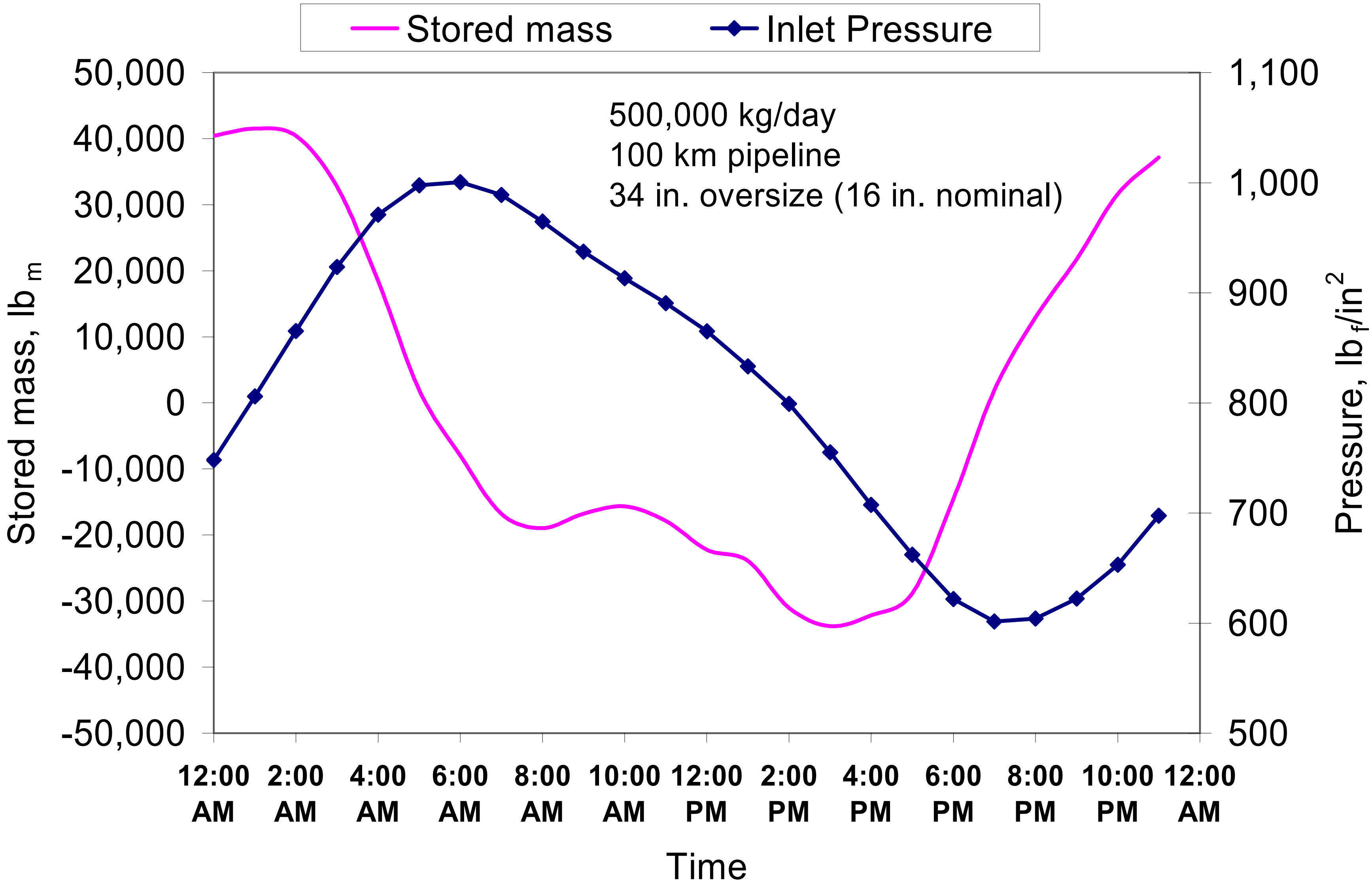




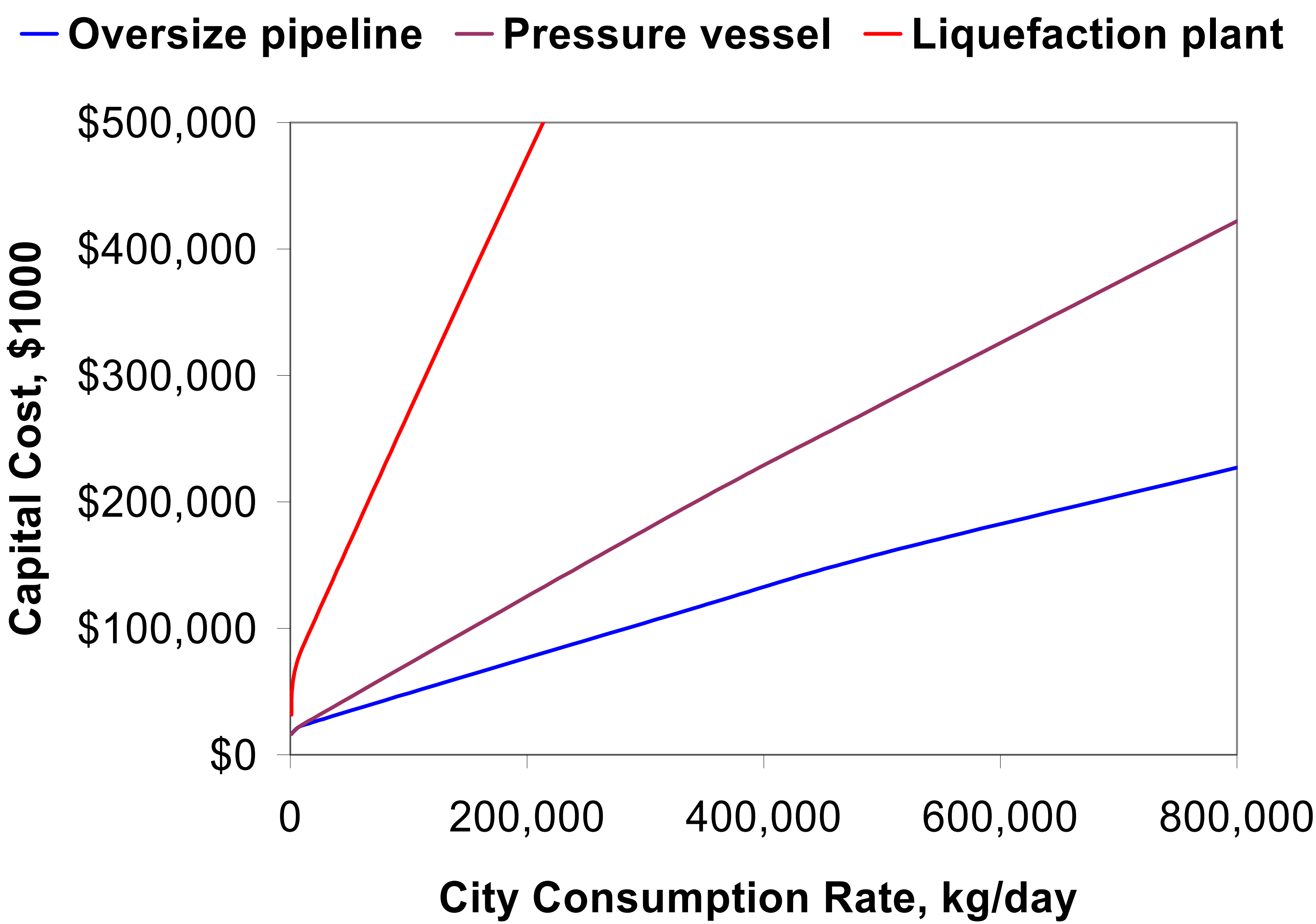




Transmission Pipeline Storage

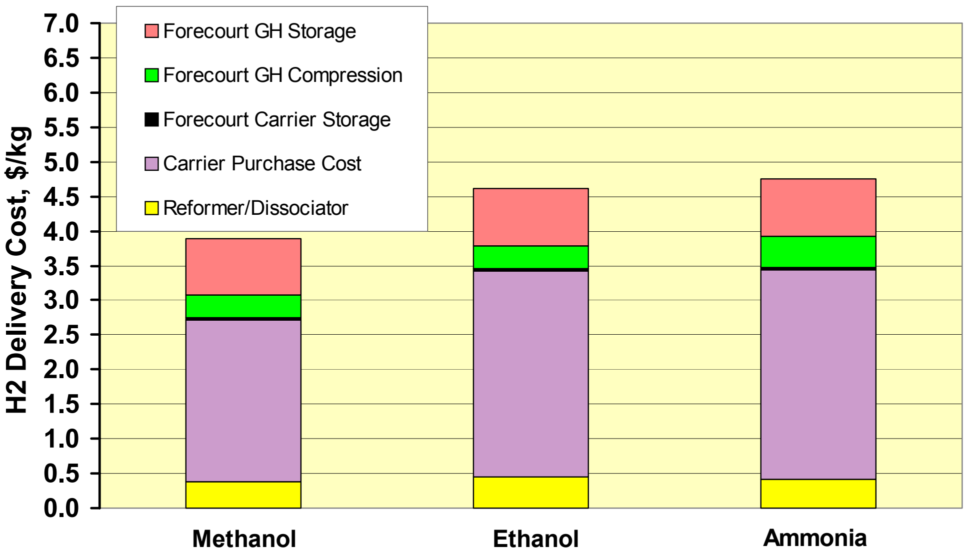


Storage to Match Forecourt Demand



Methanol, Ethanol, Ammonia as Carrier

- Forecourt conversion
  - Methanol: steam reforming
  - Ethanol: auto thermal reforming
  - Ammonia: dissociation
- Cost of hydrogen in carrier is difficult to calculate; economics can only be compared with other delivery methods by including hydrogen production costs



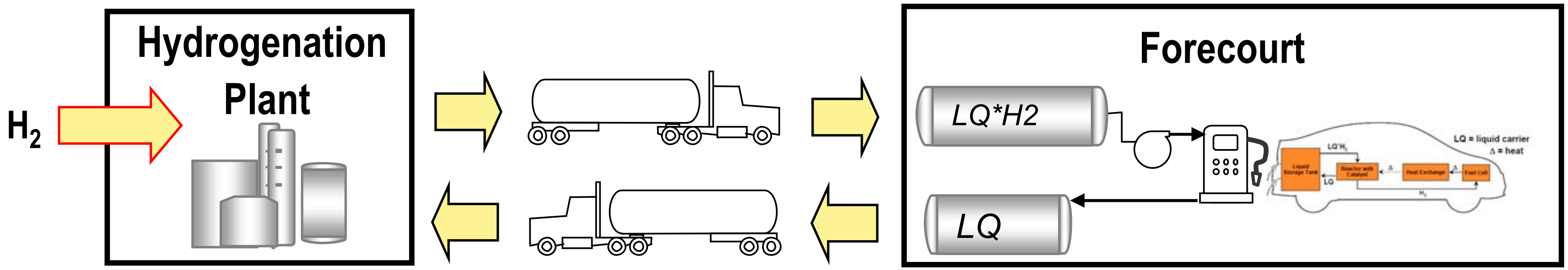
Purchase cost, $/gallon

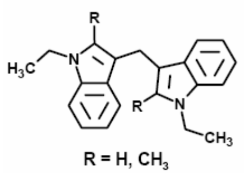
- Methanol: 0.95
- Ethanol: 1.55
- Ammonia: 0.76

Novel Hydrogen Carriers

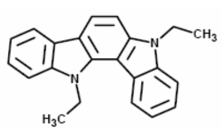
Technology	Forecourt Processing
Alanate	Dehydrogenate to produce GH
Chemical Hydride	React with H_2O to produce GH
Liquid Hydrocarbon	Pump to on-board fuel tank
Flowable Powder	Pump to on-board fuel tank
Bricks	Load as on-board fuel tank

Liquid Hydrocarbon Carrier

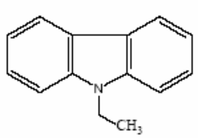




Bis-indolylmethane



Indolocarbazole



N-ethyl carbazole

Carriers explored by Air Products

- Promising option
  - High H_2 content: 5-6.5 wt%
  - Safe storage and transport
  - No forecourt gas compression
  - Delivery infrastructure in place
- On-board dehydrogenation
  - 80 C desired; 170 C to date
  - 75 C melting point
- Hydrogenation
  - Central processing
  - 170 C, 1200 psi
  - Carrier makeup/ blowdown requirement defines economics

Summary

- **Hourly variation in forecourt demand is perhaps best met by oversize transmission line**
- **Small cost benefit to converting natural gas or oil pipeline to hydrogen transmission line**
- **Limited opportunities for using natural gas / hydrogen blends during transition**
- **Liquid hydrocarbon carriers, such as being developed by Air Products, are promising**

Future Work

- Provide additional performance and cost data to Component and Scenario Models
- Evaluate capability of existing infrastructure for hydrogen delivery
- Estimate greenhouse gas and pollutant emissions in hydrogen delivery
- Estimate efficiencies, costs, and emissions of hydrogen delivery at market penetrations of 1%, 10%, 30%, 70%, and 100%
- Recommend delivery strategies at each market penetration