H2A Hydrogen Delivery Components Model

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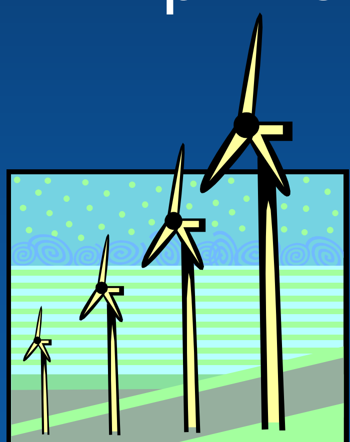
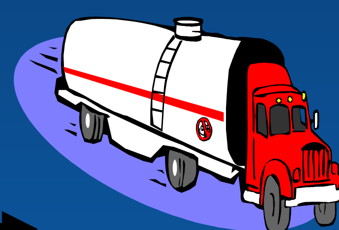
Outline

- Hydrogen delivery definition
- H2A Delivery Component Model
  - Methodology
  - Components included
  - Key Assumptions
- Spreadsheet demonstration

Hydrogen Delivery

- Hydrogen delivery and storage defined as the complete set of equipment and processes used to move hydrogen from the central production plant to the forecourt station or primary usage





Hydrogen Delivery Component Model

- Excel-based tool
- Allow the user to determine a “generic” hydrogen cost for a particular component
- Each storage and delivery component has separate tab
- Final hydrogen cost determined using fixed charge rate calculation
  - Final hydrogen cost determined in real dollars
  - Model assumes MACRS depreciation
  - Replacement capital includes for some components

Component Economic Analysis

- The economic results presented assume specific scenario
  - Scenario refers to specific situation of hydrogen storage and delivery … therefore, the results do not apply to every hydrogen storage and delivery application
  - Scenario’s used to prepare results are static and do not include dynamic cost effects likely to be applicable in real-life development of hydrogen storage and delivery infrastructure in a demand market

Consistent Assumptions Throughout Model

- Discount Rate – 10%
- Dollar Year – 2005
- Startup Year – 2005
- Depreciation Type – MACRS
- Analysis Period – 20 years
- Federal Taxes – 35%
- State Taxes – 6%
- Total Tax Rate – 38.6%

Components Modeled

- Hydrogen moved in either liquid or gaseous forms

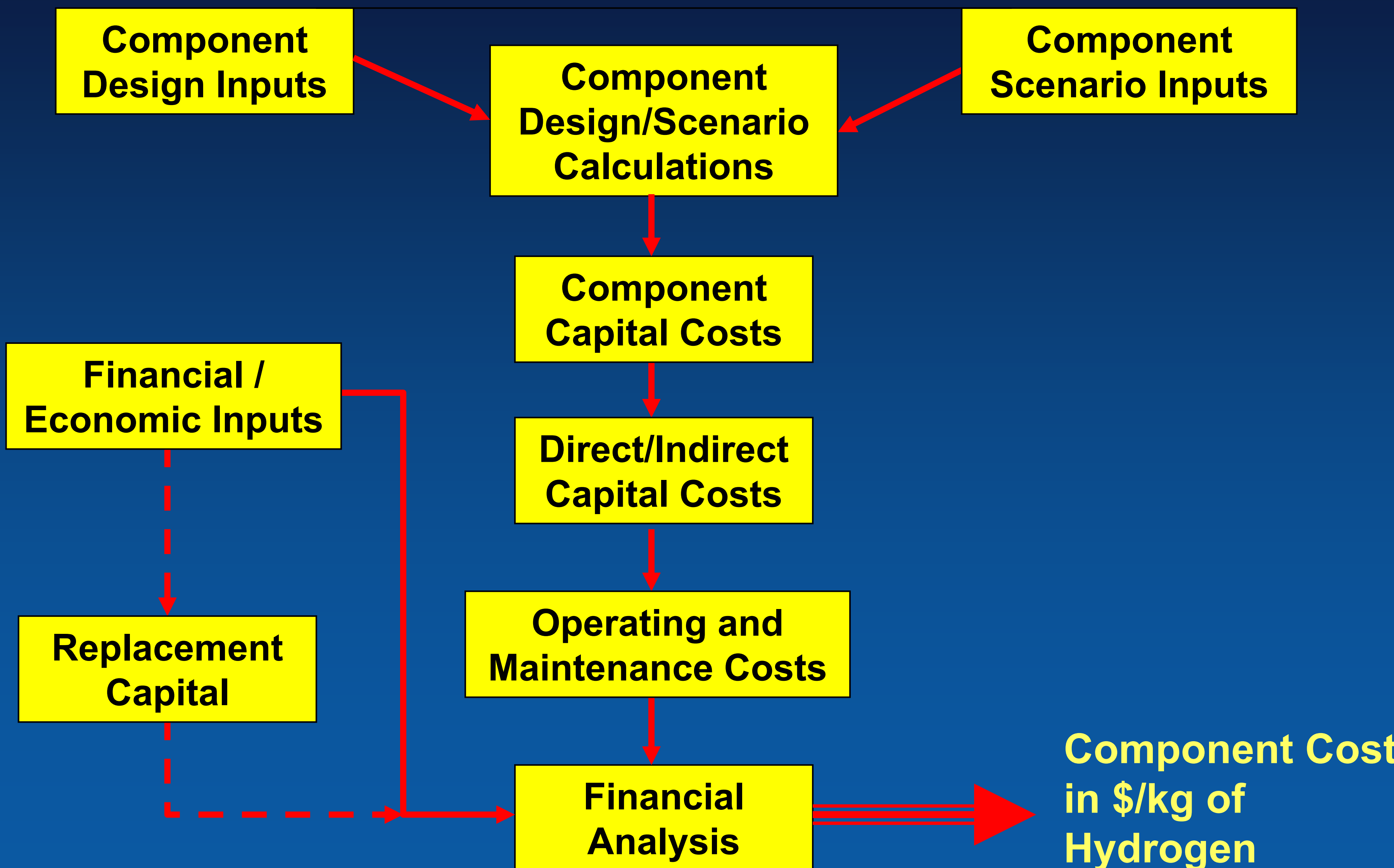
Delivery Components	Storage Components
-Truck – Tube Trailer -Truck - LH2 -Pipeline -Liquefier -Compressor (one-stage and multi-stage) -Forecourt Compressor	-Compressed Gas Tube System -Bulk Liquid Hydrogen System -Geologic -Forecourt
-Terminals (gaseous and liquid)	

Spreadsheet Features

- Yes/no toggle switches to allow for user input or H2A standard input
  - Inputs turn on/off based on yes/no toggle switch
- Error messages included to alert user when input errors are made
- Multiple options for MACRS depreciation period
  - Includes standard MACRS table
- Color-coded to facilitate user input

(light blue)	**Calculated Cells**
(orange)	**User Input Required**
(light green)	**Optional Input**
(yellow)	**Information**

Component Model Hierarchy



Component Spreadsheet Inputs

- Design Inputs
  - Inputs required to design particular component
  - Includes design hydrogen throughput, operating pressures, temperatures, component efficiency, system losses
- Scenario Inputs
  - Inputs required to design “generic” scenario for specific component
  - Includes delivery times, component availability, days of storage required, truck speed, delivery distance

Component Spreadsheet Inputs (cont.)

- Calculations
  - No inputs required; calculations required for financial analysis
- Economic Assumptions
  - Lifetime, discount rate, analysis period, taxes, depreciation period, system start-up year
- Capital Costs
  - All component capital costs
  - Options to use H2A data, or user-entered data

Component Spreadsheet Inputs (Cont.)

- Other Capital
  - Land costs (assumed depreciable)
  - Site preparation, engineering, contingency
  - Options to use H2A, Peters and Timmerhaus or other data
- O&M Costs
  - Labor, feedstock costs (from H2A cost projections, or user-entered)
  - Property taxes, insurance
- Financial Analysis
  - Calculations to get component hydrogen cost ($/kg)

Financial Analysis

- Based on fixed charge rate calculation
  - First, capital recovery factor is calculated

$$CRF = \sum_{z=1}^{N} \frac{1}{(1+d_r)^z} = \frac{d_r(1+d_r)^z}{(1+d_r)^z - 1}$$

D = discount rate, N=analysis period

  - Present value of depreciation charges for particular MACRS recovery period calculated

Financial Analysis (cont.)

- Fixed Charge Rate Calculation
  - Based on before-tax-required formula

$$FCR = \frac{CRF\left(1 - bT\sum_{n=1}^{M}\frac{V_n}{(1+d_n)^n} - t_c\right)}{(1-T)}$$

b=fraction dep. base, T=total tax rate, V_n=fraction of dep. base in year n, t_c=tax credits

$$FCR = \frac{CRF(1 - T * D)}{(1-T)}$$

D=present value of depreciation (MACRS), T=total tax rate

Financial Analysis (cont.)

- Capital multiplied by FCR; product added to sum of annual costs (labor, utilities, other O&M)
  - Gives required revenue
- Required revenues calculated then divided by actual hydrogen throughput in a year for component
  - $/kg of H2 cost

Compressed Gas Truck Delivery

- Calculations assume trailer is dropped off at station
- Tab designed based on one tractor and enough trailers to maximize tractor utilization
- Analysis period = 20 yrs

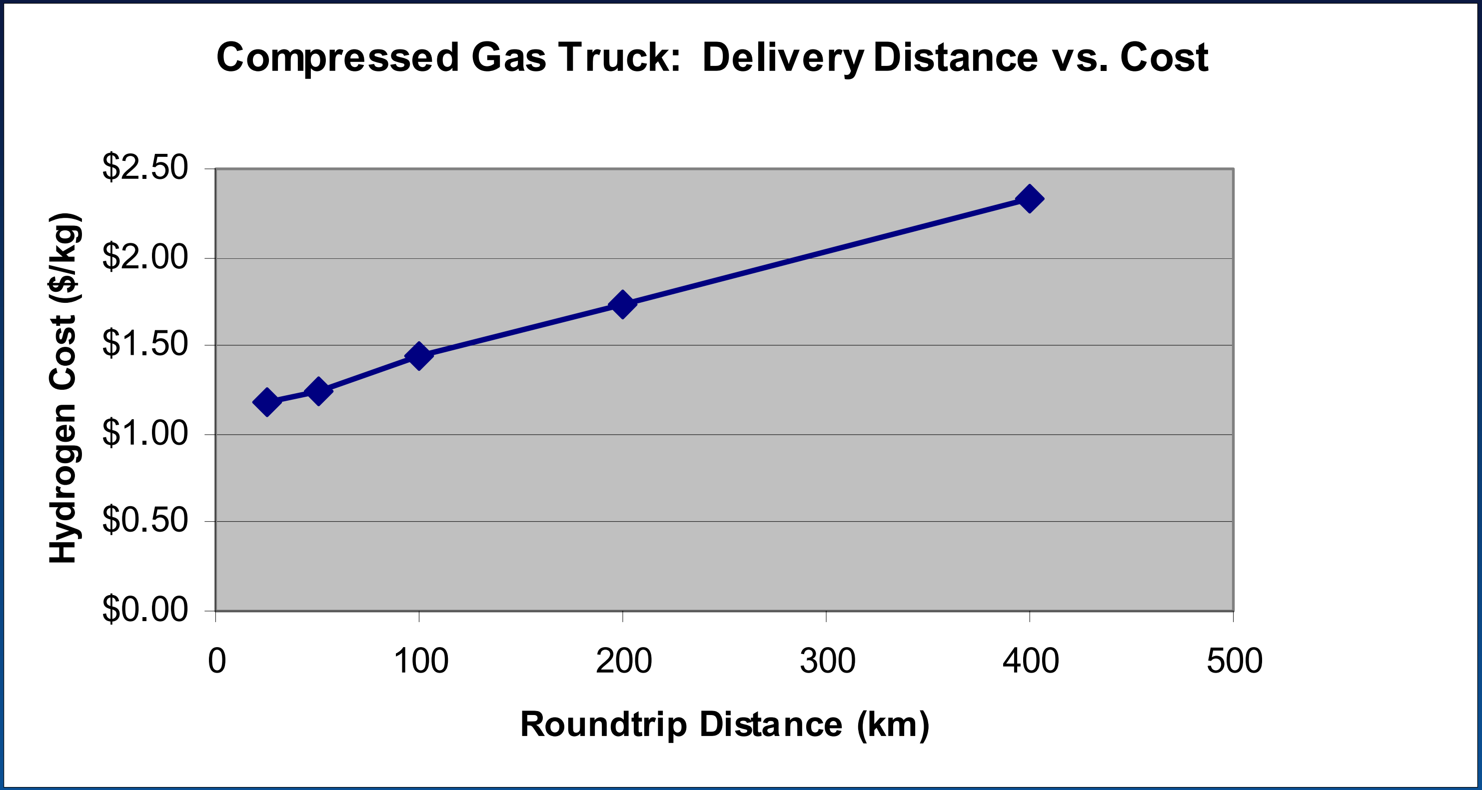
Compressed Gas Truck (cont.)

- Trailer assumptions (H2A KIC):
  - Max P = 2,640 psig, Min P = 135 psig
  - Super Jumbo trailer holds 9 tubes, total of 340 kg of H2
  - Lifetime - 20 yrs, MACRS Schedule - 5 yrs
  - Capital Cost - $165,000 (year 2005 dollars)
- Tractor assumptions:
  - Avg. speed – 50 km/hr (30 mph)
  - Fuel economy – 2.6 km/L (6 mpg)
  - Lifetime - 5 yrs; MACRS schedule – 5 yrs
  - Capital Cost - $165,000 (year 2005 dollars)
    - No overnight coach

Compressed Gas Truck Cost

- Scenario assumptions:
  - Loading time at terminal – 6 hrs
  - Drop-off/Pick-up time – 2 hrs
- Roundtrip Delivery Distance – 100 km
  - H2 Station demand – 100 kg/day
  - Trailers required – 16
- Compressed Gas Truck Portion of Delivered H2 Cost
  - $1.44/kg of hydrogen
  - $0.83/kg for capital, $0.04/kg for fuel, $0.56 for other (includes labor)

H2A Delivery

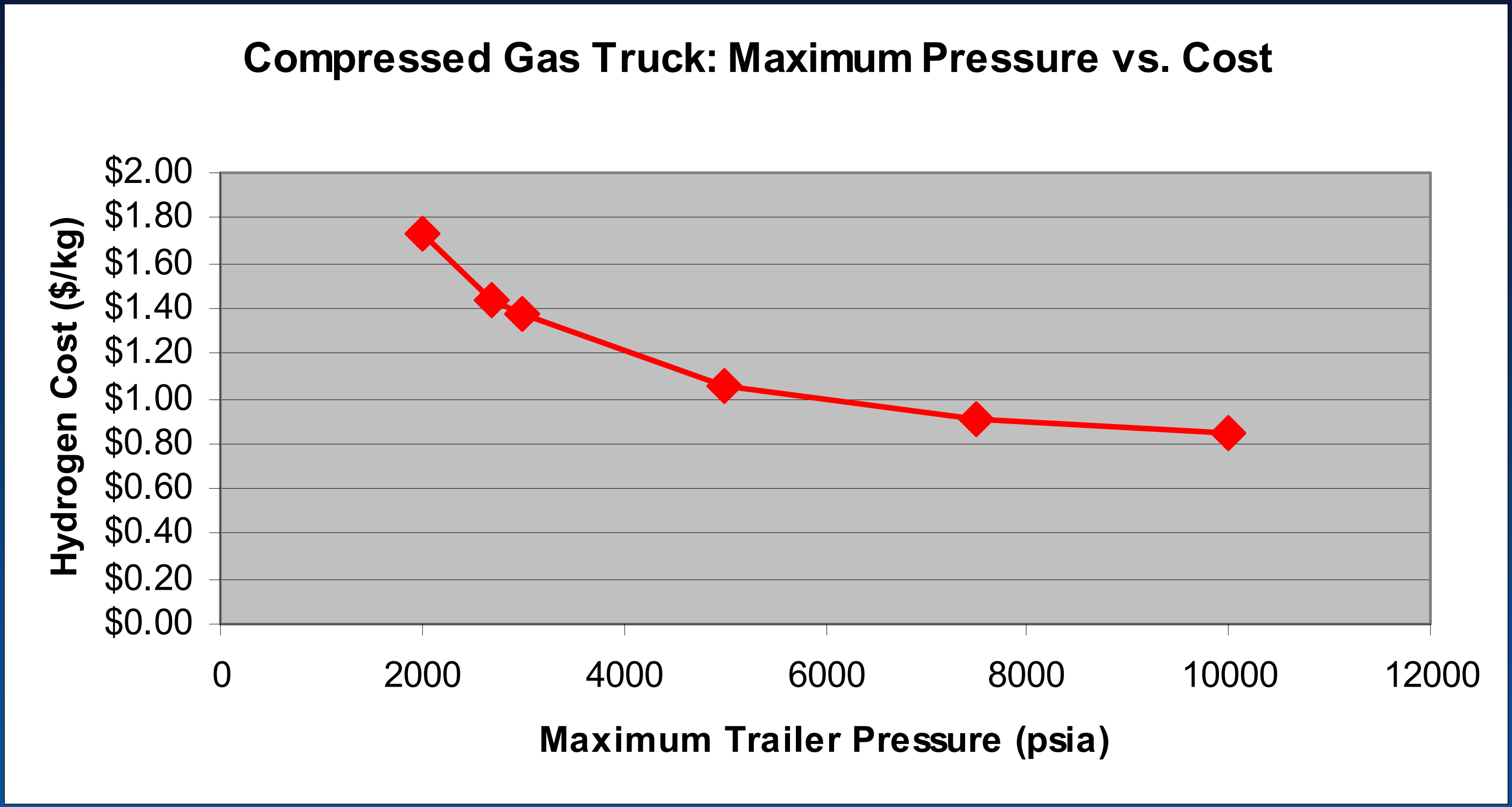


Assumptions:

Maximum Pressure: 180 atm

Station Demand: 100 kg/day

H2A Delivery



Assumptions:

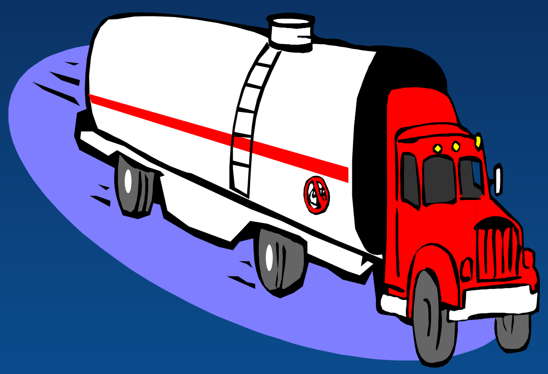
Delivery Distance: 100 km

Station Demand: 100 kg/day

Spreadsheet Demonstration

Liquid H2 Truck Delivery

- Design based upon 1 tractor and 1 trailer
  - Flexibility to specify 1, 2 or 3 stops
- Storage assumed to exist at delivery site
- Same tractor/scenario assumptions as gas truck delivery



LH2 Truck Delivery Cost

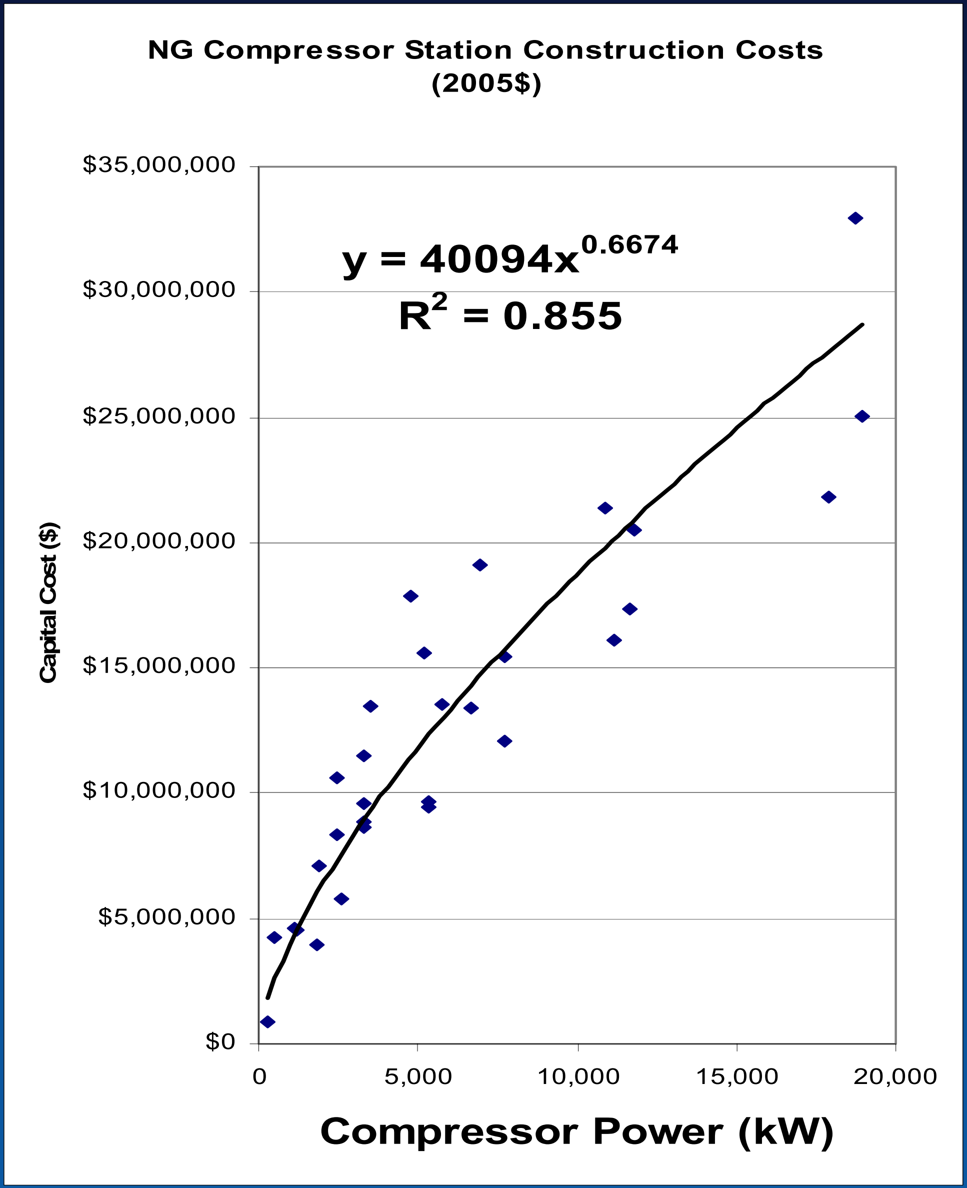
- Trailer assumptions:
  - Capacity – 17,000 gall (3,800 kg of H2)
  - Unloading/Loading losses – 6%
  - Lifetime – 20 yrs; MACRS Depreciation – 5 yrs
  - Capital cost - $715,000 (year 2005 dollars)
- Roundtrip Delivery Distance – 100 km
  - H2 Station demand – 1,500 kg/day
  - Number of stops – 2 per trip
- LH2 Truck Portion of Delivered H2 Cost
  - $0.24/kg of hydrogen
  - $0.13/kg for capital, <$0.01/kg for fuel, $0.11 for other (includes labor)

Compressor (Single, Multi-stage and Forecourt)

- Based on one compressor
- User can input adiabatic efficiency and have power req. calculated, or enter power required in kWh/kg of H2
- Analysis period - 20 yrs
- Compressor assumptions:
  - 90% availability
  - Cp/Cv – 1.4 (for H2 compression)
  - Adiabatic efficiency – 70%
  - Lifetime – 5 yrs; MACRS Schedule – 5 yrs

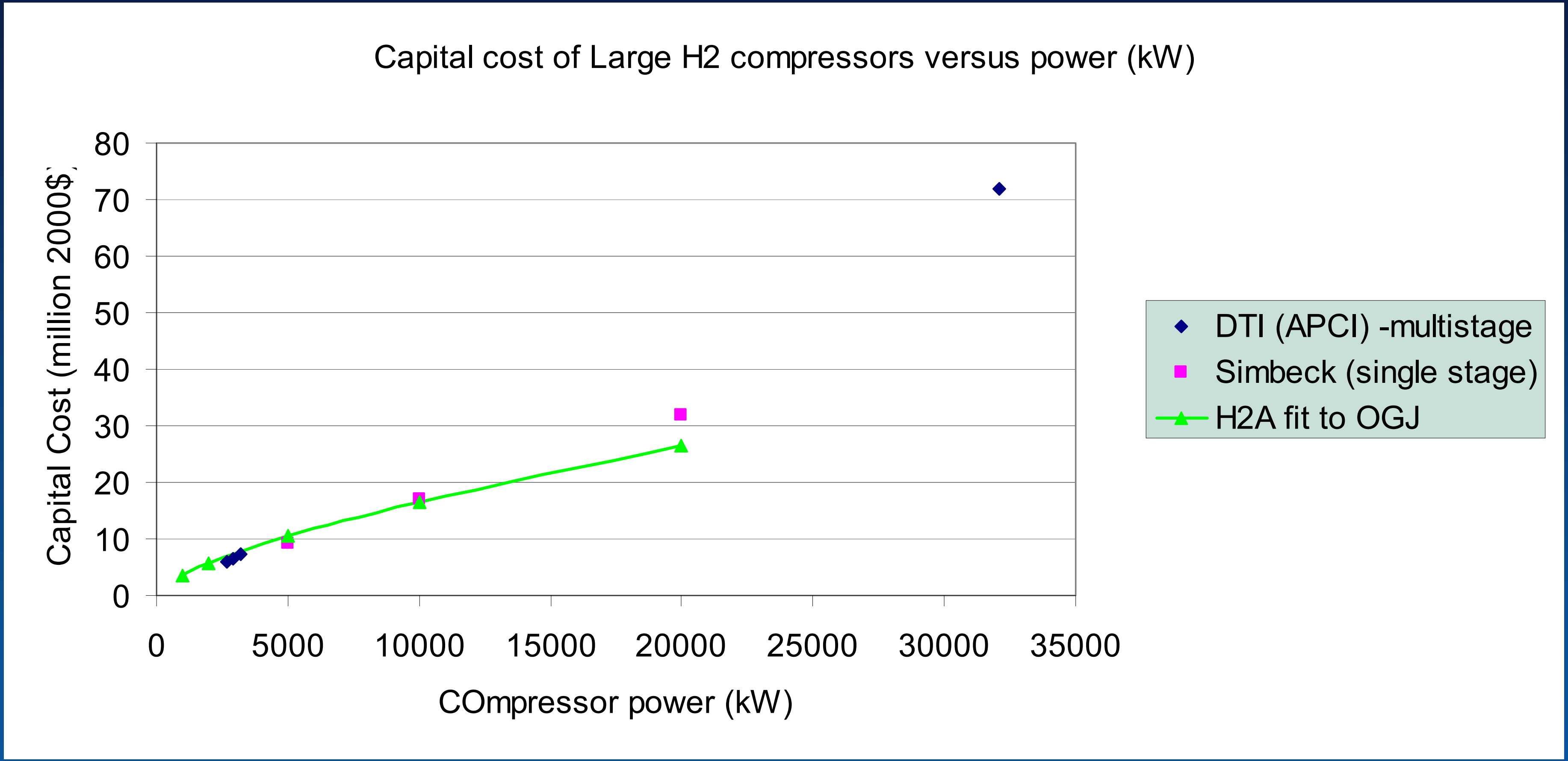
From American Gas Compression Services website

H2A Delivery



Data from Oil and Gas Journal Report on Pipelines, 2000

H2A Delivery



Compressor Cost

- Larger scale compressor
  - Design capacity – 300,000 kg/day
  - Inlet pressure – 20 atm (295 psia)
  - Outlet pressure – 70 atm (1,030 psia)
  - Pressure ratio – 1.7, 3-stages
- Compressor Portion of Delivered H2 Cost
  - $0.12/kg of hydrogen ($21MM capital)
  - $0.06/kg for capital, $0.05/kg for energy, $0.01 for other (includes labor)

Forecourt Compressor

- Design parameters
  - – Design capacity – 1,500 kg/day
  - – Inlet pressure – 20 atm (295 psia)
  - – Outlet pressure – 340 atm (5,000 psia)
  - – Pressure ratio – 2.5, 4-stages
- Forecourt Compressor Portion of Delivered H2 Cost (2 compressors)
  - – $0.54/kg of hydrogen ($600,000 capital)
  - – $0.35/kg for capital, $0.13/kg for energy, $0.06 for other (includes labor)

Pipeline Delivery

- Tab does not design pipeline network for the user
  - Asks for transmission, trunk and distribution details

From Praxair 2003 Annual Report

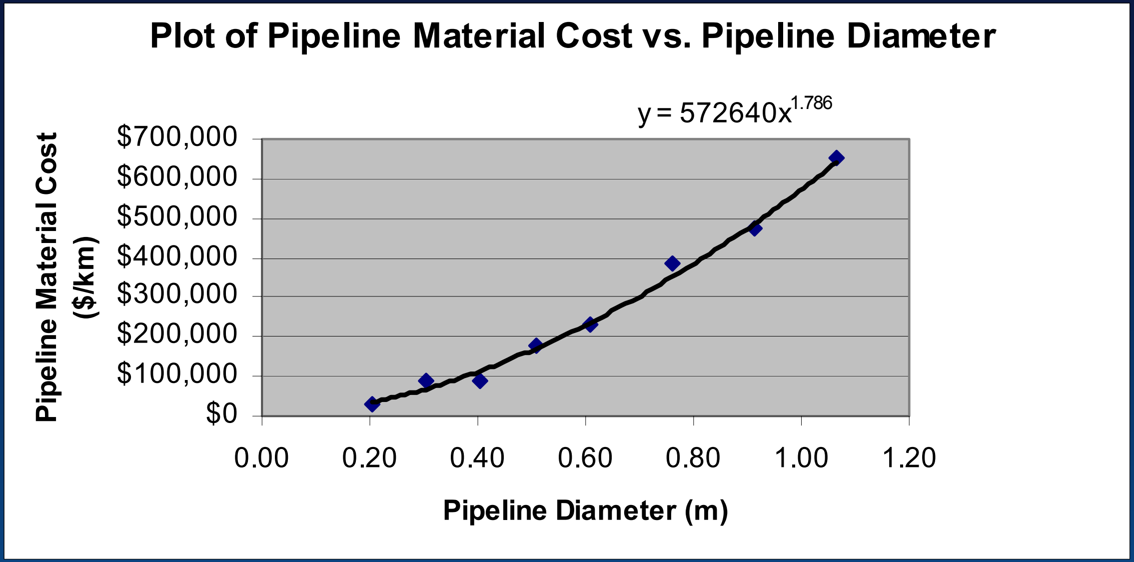
Pipeline Delivery

- Can calculate diameter or outlet pressure
  - Calculations based on Panhandle B Equation

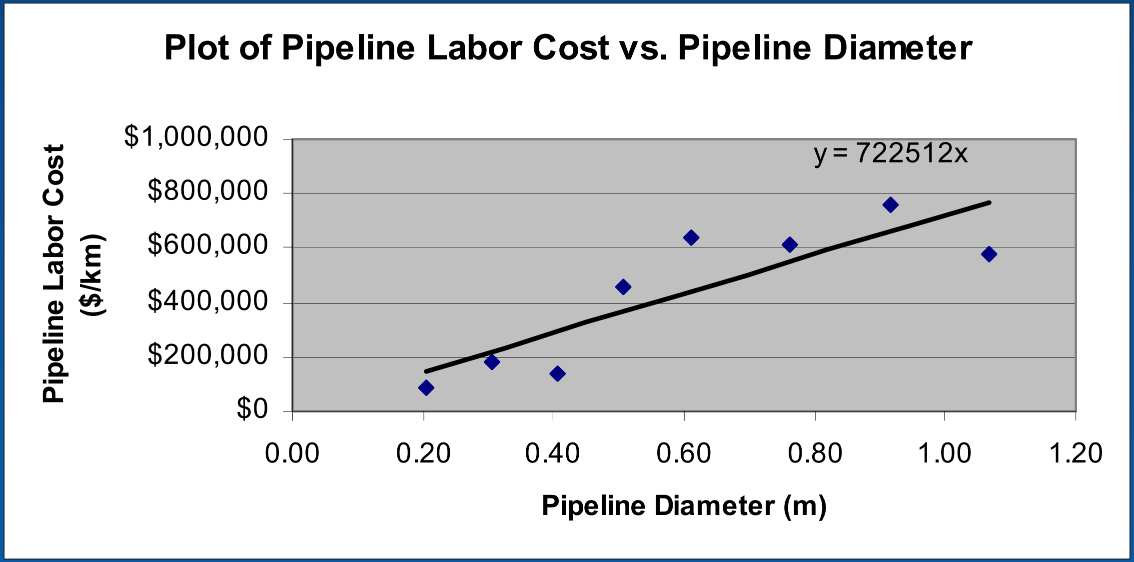
$$q_{sc} = 737\left(\frac{T_{sc}}{P_{sc}}\right)^{1.02}\left[\frac{(P_1^{\,2} - P_2^{\,2})d^{4.961}}{\gamma^{0.961} L T_m Z_m}\right]^{0.51} E$$

q_{sc}=flowrate (scfm); T_{sc}=temp at STP (R); P_{sc}=press at STP.; P_1=inlet press. (psia); P_2=outlet press. (psia); d=diameter (in); γ=gas relative density; L=length (mi); T_m=mean temp. (R); Z_m=mean compressibility factor; E=pipeline efficiency

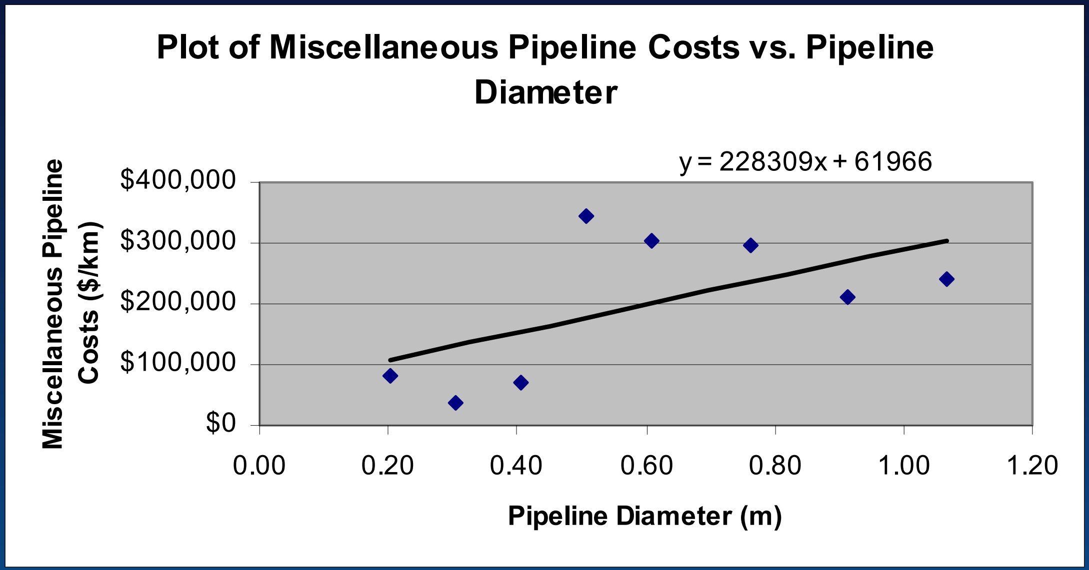
H2A Delivery



Data from Oil and Gas Journal Report on Pipelines, 2003



H2A Delivery



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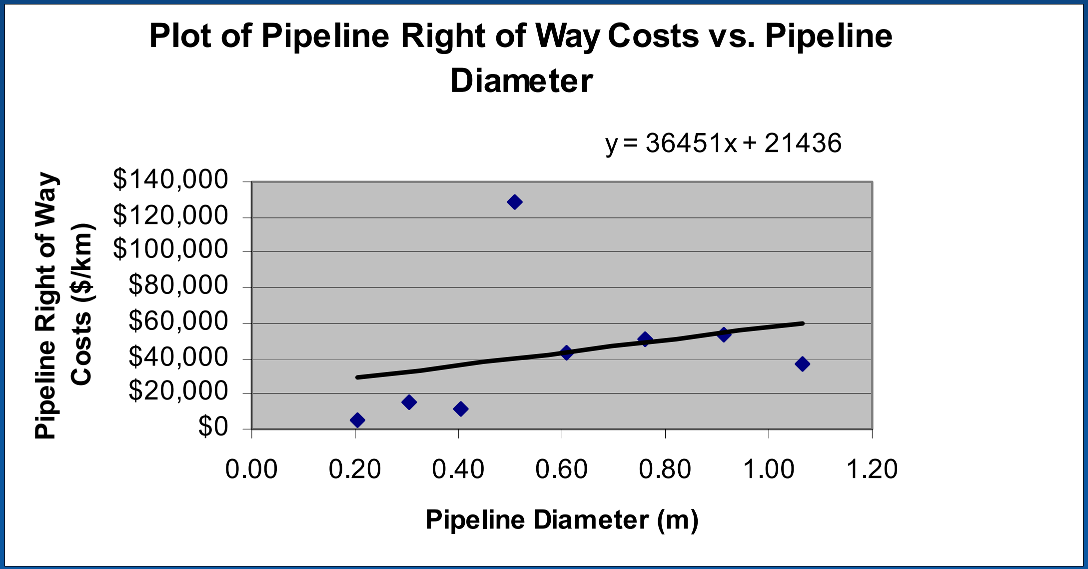
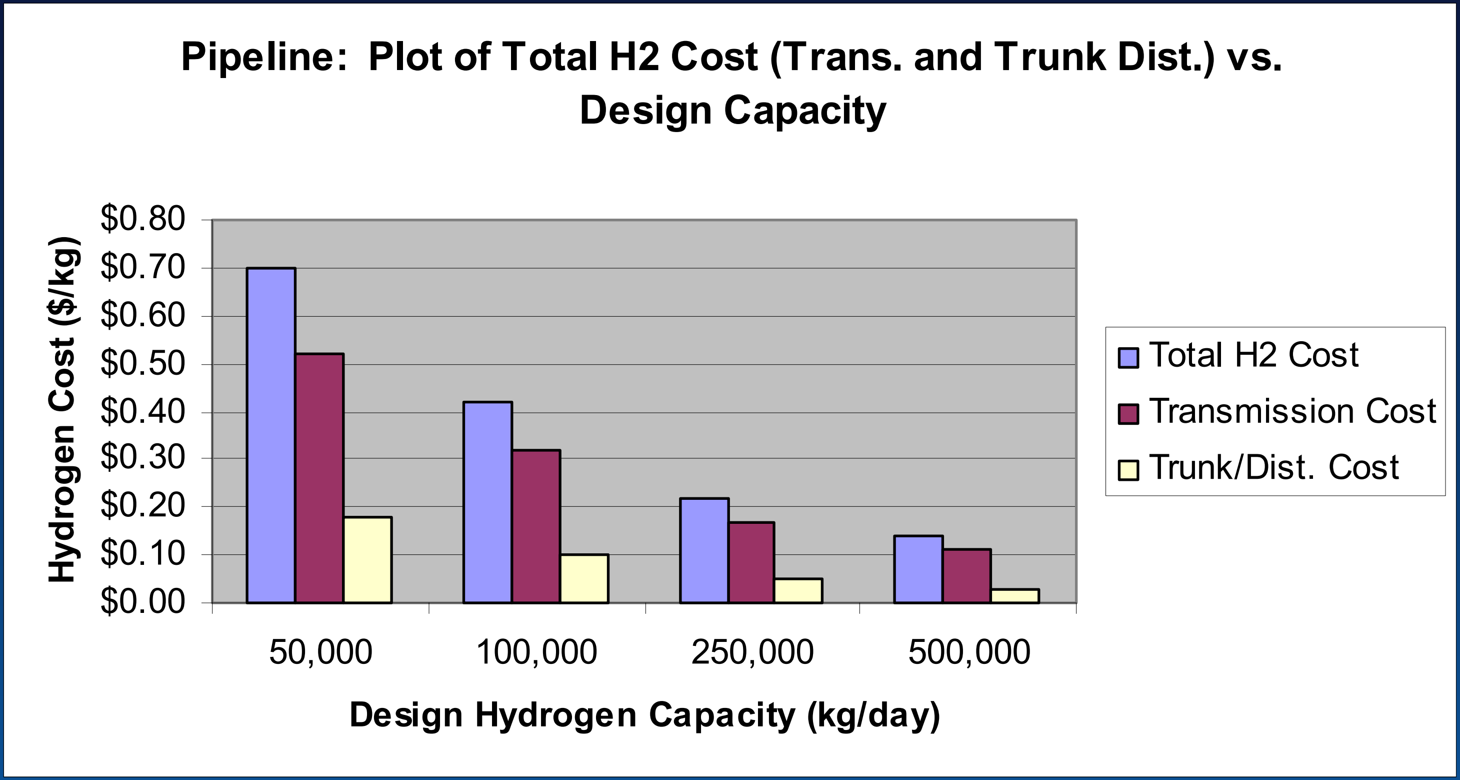


H2A Delivery

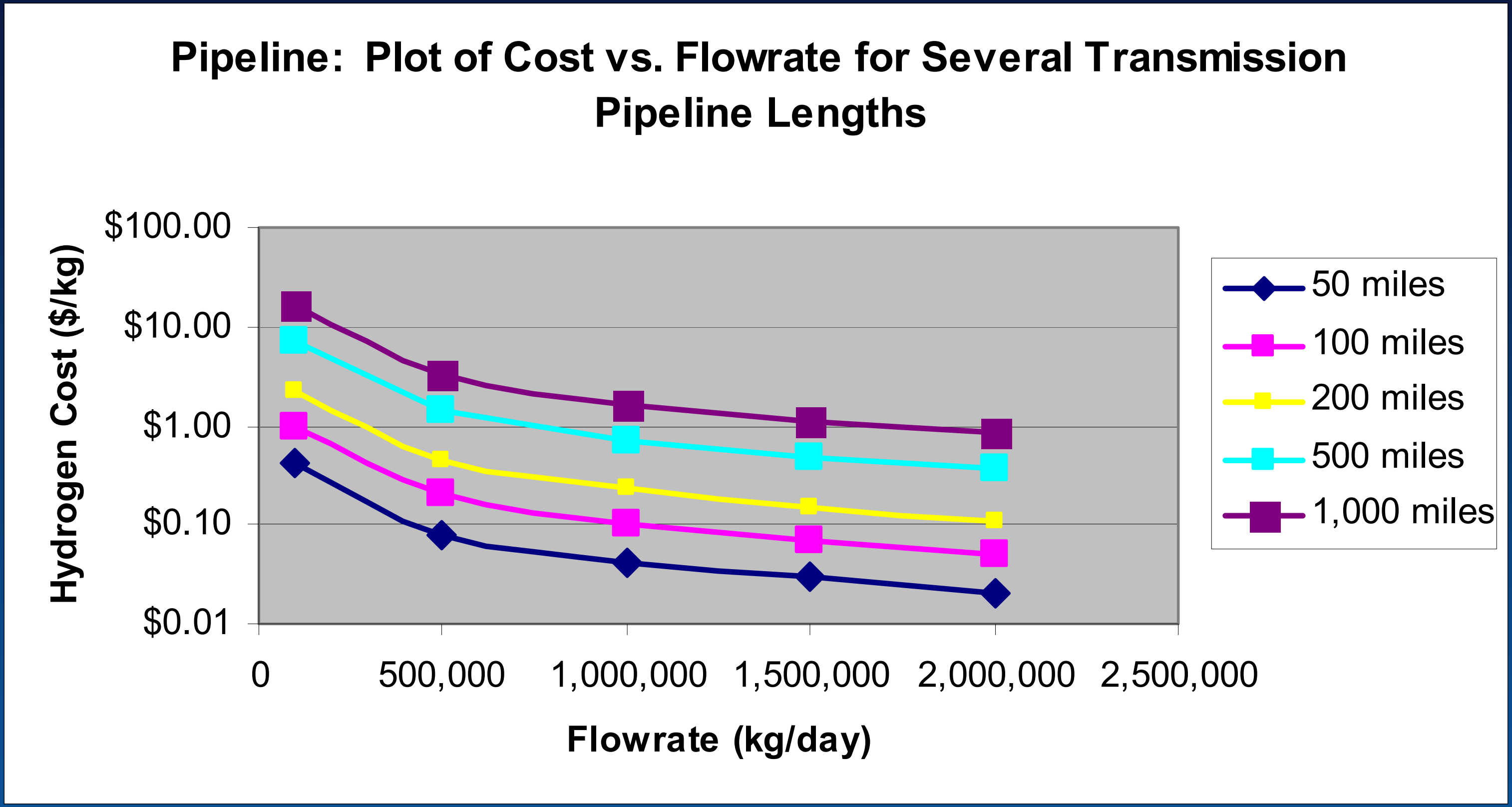


Assumptions:

Pipeline Set-up: 100 mi Transmission, 5x5 mi trunk lines, 20x2 mi distribution lines

Diameters sized based upon pressure drops: Transmission (1,000 – 700 psia), trunk (600-450 psia), distribution (400-300 psia)

H2A Delivery



Assumptions:

Pipeline diameter for each length calculated at maximum flowrate, assuming pressure drop of 300 psi (1,000 – 700 psi)

Diameters: 50 mi (20 in), 100 mi (23 in), 200 mi (24 in), 500 mi (32 in), 1,000 (37 in)

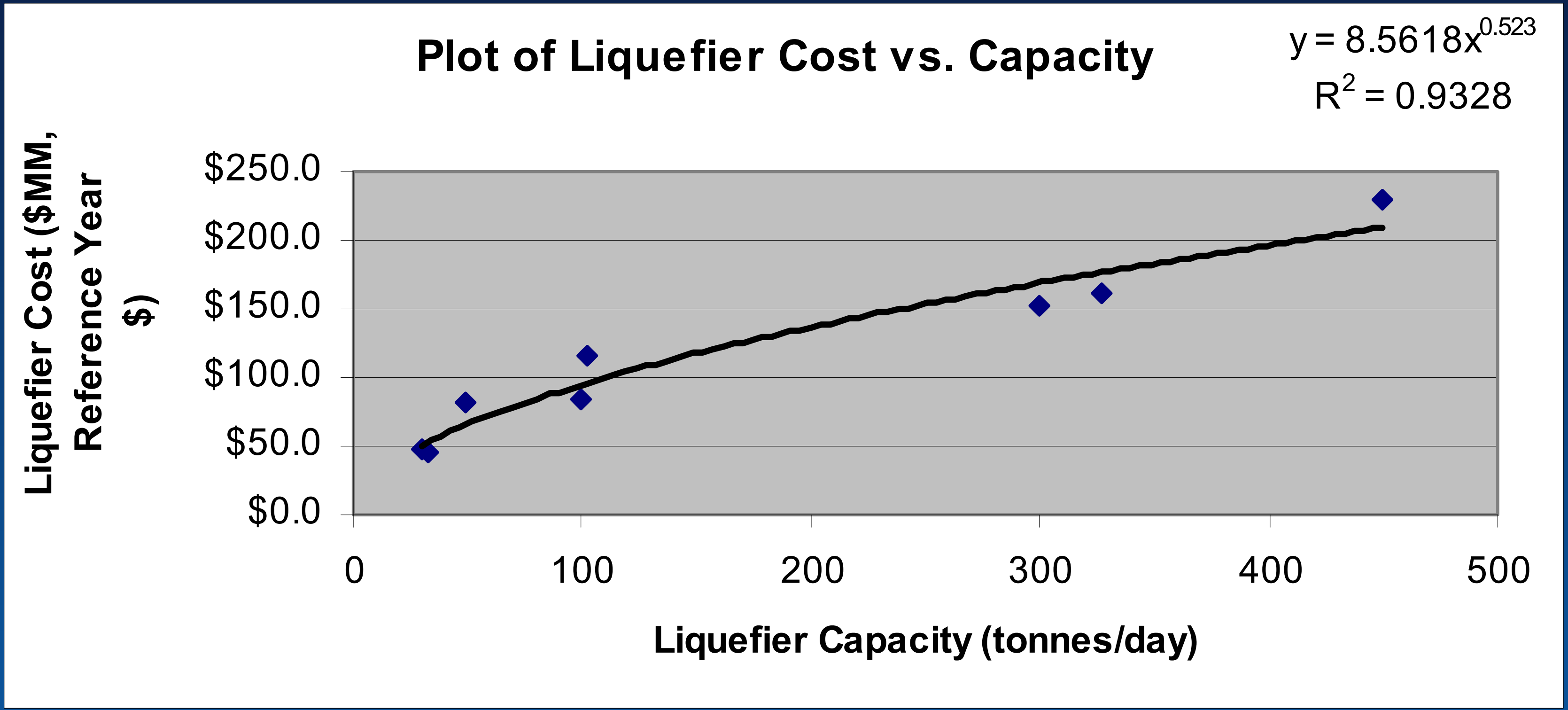
H2A Delivery

Liquefier

- Allows user to specify power requirement (kWh/kg of H2) or have power calculated
- Analysis period – 20 yrs

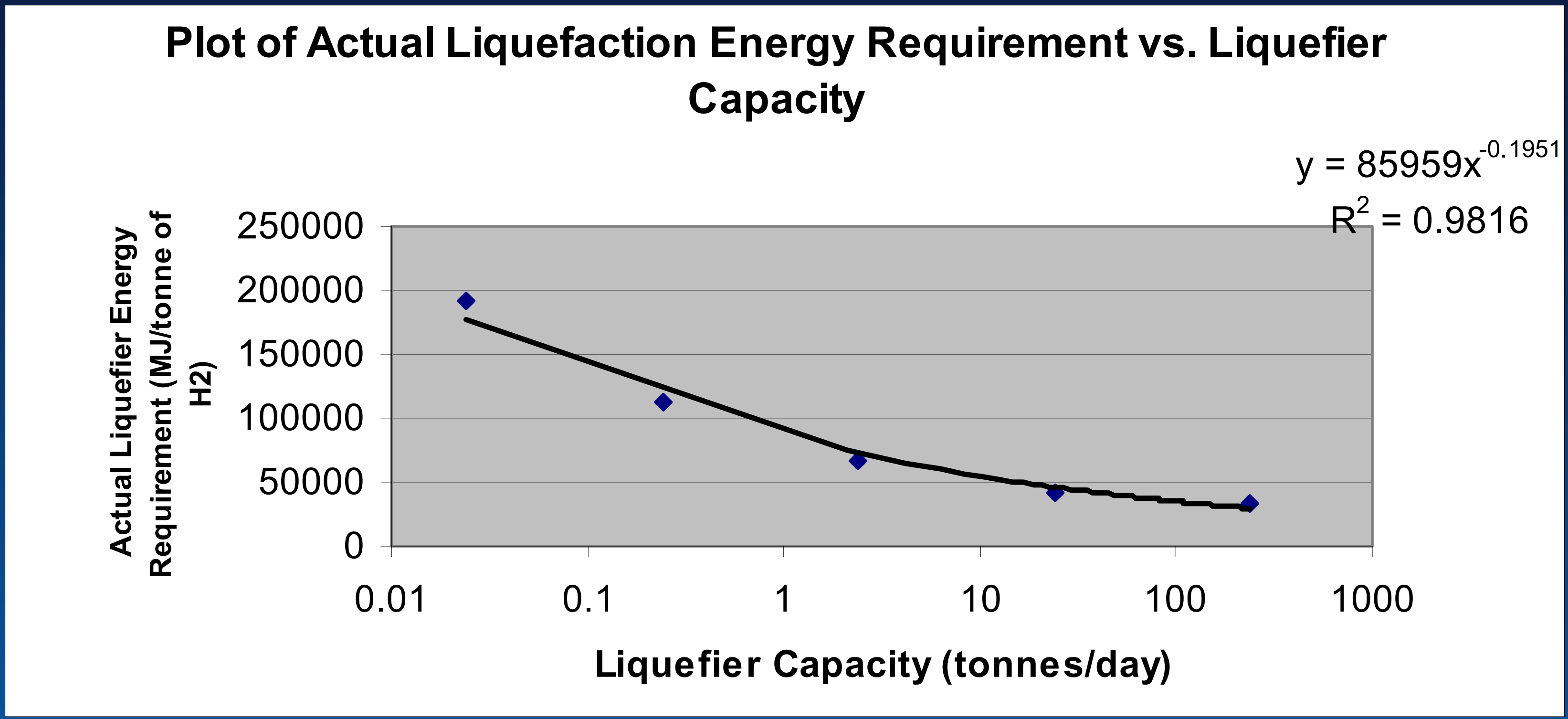
From Praxair 2003 Annual Report

H2A Delivery



Data from Taylor, 1986; Simbeck, 2002; DTI, 1997

H2A Delivery

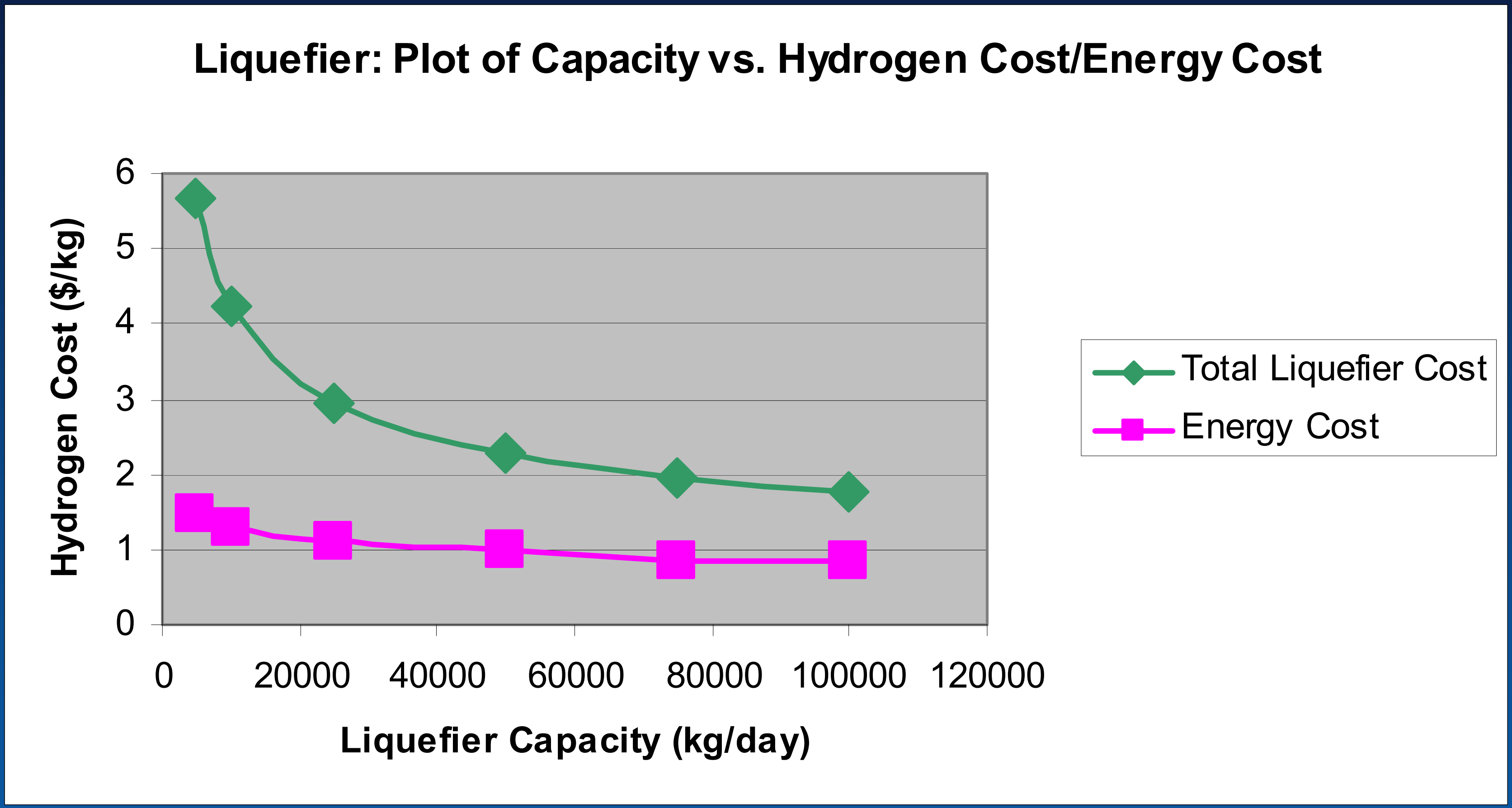


Data from Bossel et al., 2003

Liquefier – Cost

- Liquefier assumptions:
  - Design flowrate – 50,000 kg/day
  - Availability – 90%
  - Lifetime – 20 yrs; MACRS schedule – 15 yrs.
- Liquefier Portion of Delivered H2 Cost
  - \$2.27/kg of hydrogen (\$66MM capital)
  - \$1.01/kg for capital, \$0.95/kg for energy, \$0.31 for other (includes labor)

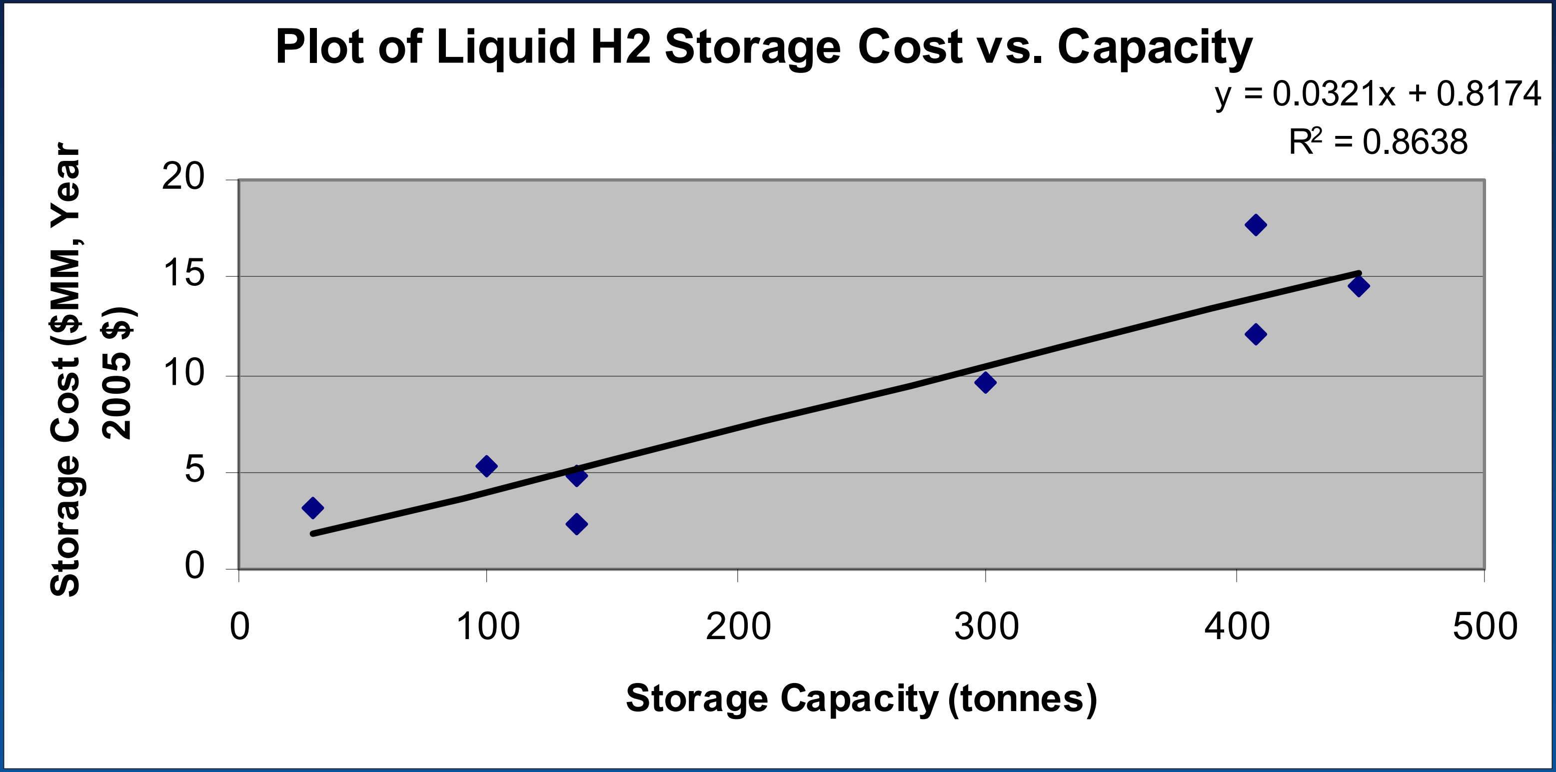
H2A Delivery



Bulk Liquid Hydrogen Storage

- Allows user to size storage based on system throughput and days of storage, or system throughput and tank size
- Analysis period – 20 years

H2A Delivery



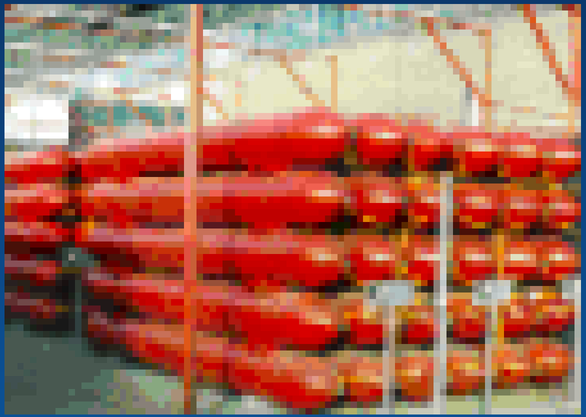
Data from Taylor, 1986; Simbeck, 2002; DTI, 1997

Bulk Liquid Hydrogen Storage

- Liquid Storage:
  - Design capacity – 50,000 kg/day, 2 days storage
  - Useable portion of tank – 90%
  - Boil-off – 0.25%/day
  - Lifetime – 20 yrs; MACRS Schedule – 7 yrs.
- Bulk Liquid Hydrogen Storage Portion of Delivered H2 Cost
  - $0.08/kg of hydrogen ($4MM capital)
  - $0.06/kg for capital, $0.02 for other (includes labor)

Compressed Gas Storage (Tubes)

- Allows user to size storage based on system throughput and days of storage, or system throughput and tank size
- Analysis period – 20 yrs



From Linde website

Compressed Gas Storage - Costs

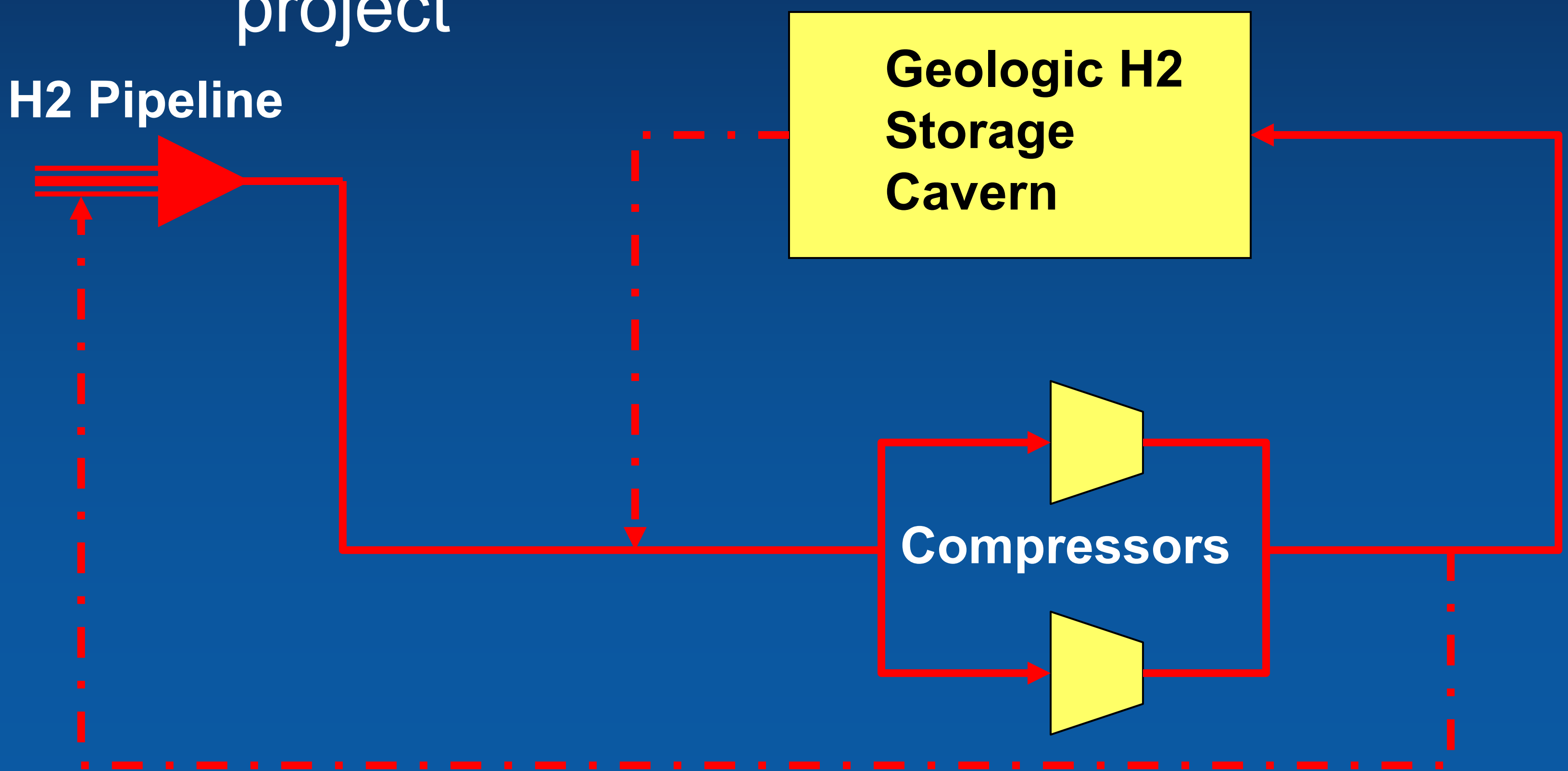
- Key assumptions:
  - Design Flowrate – 50,000 kg/day, 2 days storage
  - Max. Pressure – 415 atm (6000 psia)
  - Min. Pressure – 10 atm (150 psia)
  - Lifetime – 20 yrs; MACRS Schedule – 15 yrs.
  - Capital cost – based on quote for 358 kg tank for $127,000, 0.8 scaling factor
- Compressed Gas Storage Portion of Delivered H2 Cost
  - $0.30/kg of hydrogen ($17MM capital)
  - $0.24/kg for capital, $0.06 for other (includes labor)

Forecourt Compressed Gas Storage - Costs

- Key assumptions:
  - Design flowrate – 1,500 kg/day, 2 days storage
  - Max. Pressure – 415 atm (6000 psia)
  - Min. Pressure – 10 atm (150 psia)
  - Lifetime – 20 yrs; MACRS Schedule – 15 yrs.
  - Capital cost – based on quote for 358 kg tank for $127,000, 0.8 scaling factor
- Compressed Gas Storage Portion of Delivered H2 Cost
  - $0.34/kg of hydrogen ($790,000 capital)
  - $0.26/kg for capital, $0.08 for other (includes labor)

Geologic Compressed Gas Storage

- Based on natural gas cavern storage
  - Data came from Saltville Salt Cavern project



Geologic Compressed Gas Storage

- Based on natural gas cavern storage
  - Data came from Saltville Salt Cavern project
- Compressors can fill cavern/dispense to pipeline
  - Designed based on greater pressure ratio
  - Designed to handle complete flowrate, but operate differently
- Cavern completely filled, then completely emptied

Spreadsheet Demonstration

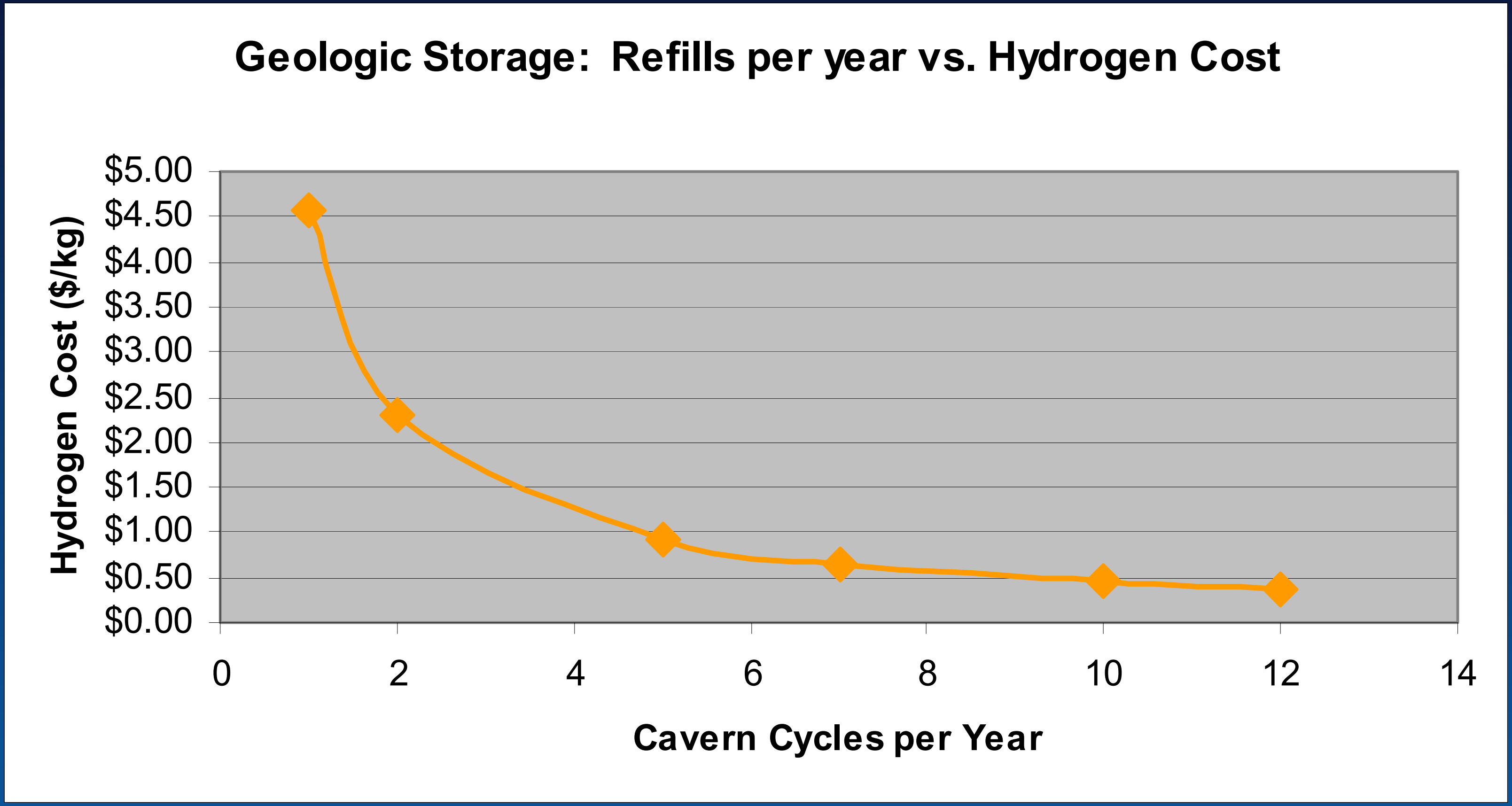
Geologic Compressed Gas Storage

- Key assumptions
  - Max. cavern pressure – 125 atm (1,850 psia)
  - Min. cavern pressure – 20 atm (300 psia)
  - Design flowrate – 500,000 kg/day, 10 days storage
  - Time to fill cavern – 15 days
  - Time to drain cavern – 10 days

Geologic Compressed Gas Storage - Cost

- Economic parameters
  - Analysis period – 20 years
  - Compressor lifetime – 5 yrs.; MACRS Depreciation Schedule – 5 yrs
  - Cavern lifetime – 20 yrs.; MACRS Depreciation Schedule – 15 yrs
- Compressed Gas Storage Portion of Delivered H2 Cost
  - $0.46/kg of hydrogen ($0.39 for compressors/$0.07 for cavern)
  - $0.39/kg for capital, $0.01 for energy, $0.06 for other (includes labor)

H2A Delivery



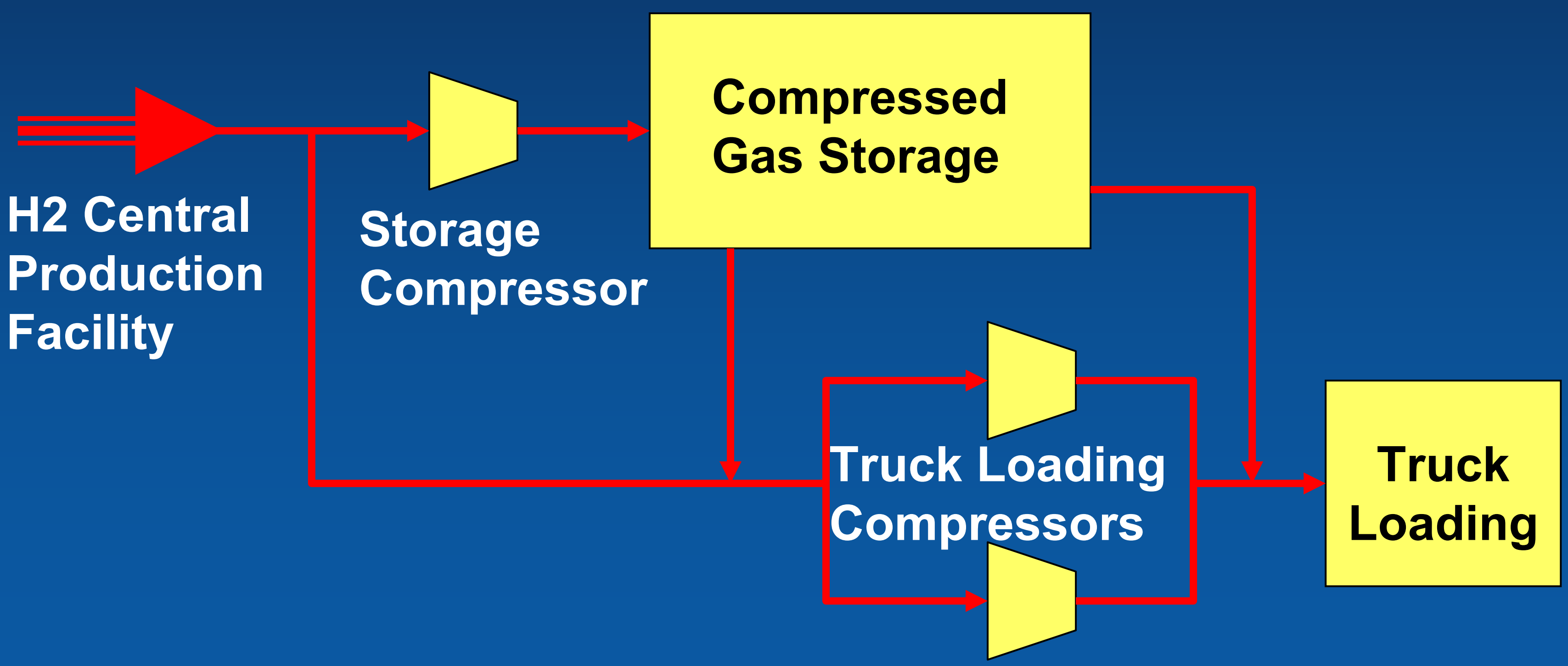
Assumptions:

Time to refill – 15 days

Time to empty – 10 days

Compressed Gas Terminal

- Designed like mini-scenario
- Setup



Compressed Gas Terminal (cont.)

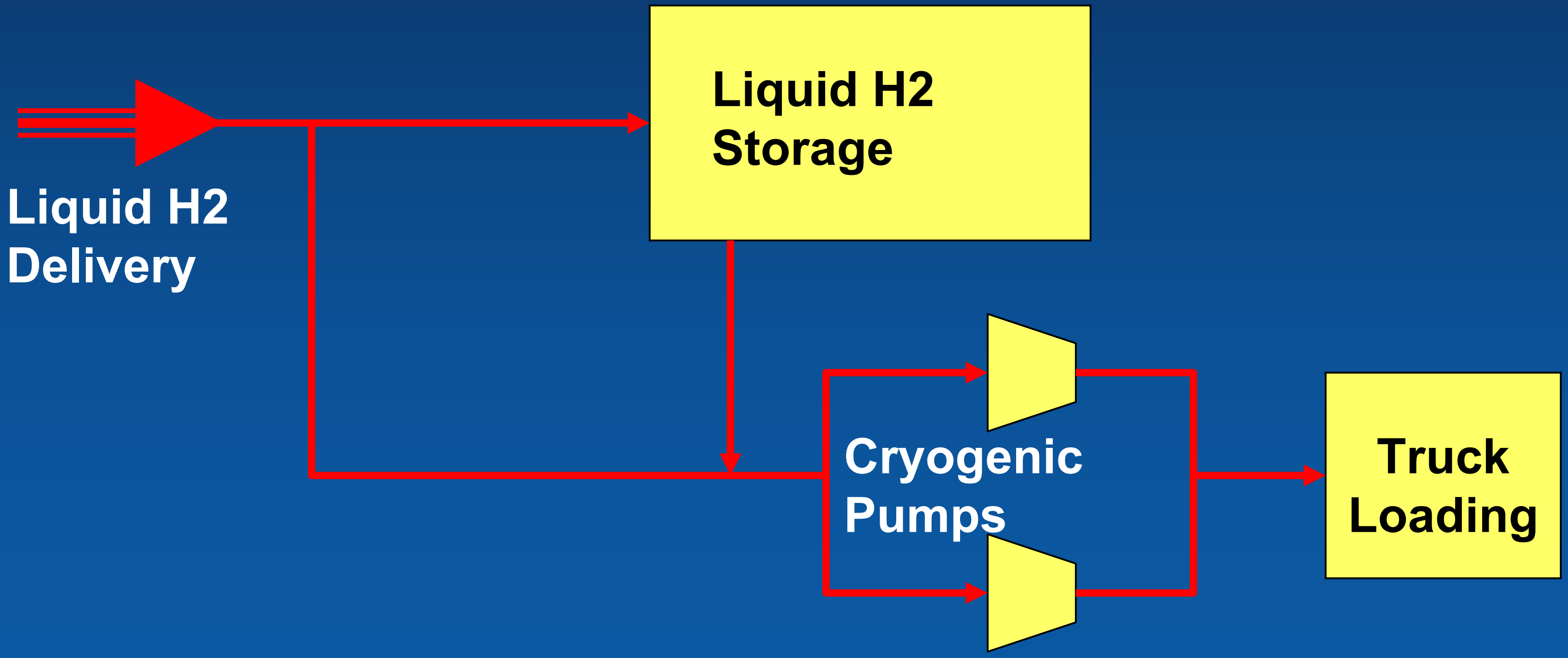
- Truck loading compressors: 2, each designed at 75% of total terminal capacity
- Storage compressor: 1, designed for filling storage tank in 1 day
- Analysis period – 20 yrs.

Compressed Gas Terminal - Costs

- Key assumptions:
  - Storage press. – 6,000 psia
  - Compressor adiabatic efficiency – 70%
  - Compressor lifetime – 5 yrs
  - Storage lifetime - 20 yrs
  - Truck filling time – 6 hours
- Compressed Gas Storage Portion of Delivered H2 Cost
  - $0.89/kg of hydrogen ($0.64 for compressors/$0.25 for storage)
  - $0.59/kg for capital, $0.16 for energy, $0.14 for other (includes labor)

Liquid H2 Terminal

- Designed like mini-scenario
- Setup



Liquid H2 Terminal

- Liquid hydrogen pumps – 2 cryogenic pumps, each designed at 75% of the total terminal capacity
- Key assumptions:
  - Design flowrate – 500,000 kg/day; 5 days of storage
  - Boil-off – 0.25% per day
  - Lifetime – 20 yrs; MACRS Schedule – 15 yrs

Liquid H2 Terminal - Costs

- Key assumptions (continued):
  - Truck filling time – 3 hours
- Compressed Gas Storage Portion of Delivered H2 Cost
  - $0.20/kg of hydrogen ($89MM capital for storage, $7MM for low temperature pumps)
  - $0.15/kg for capital, $0.05 for other (includes labor)

Conclusions

- Spreadsheet model has been developed to calculate cost, in \$/kg of H_2, for delivery components
- Based on fixed charge rate financial analysis method
- Meant to model static delivery cases
- Base case assumptions introduced
  - Detailed cost curves, based on vendor, literature data, developed for some components