Hydrogen Delivery Analysis Meeting
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Forecourt and Gas Infrastructure Optimization

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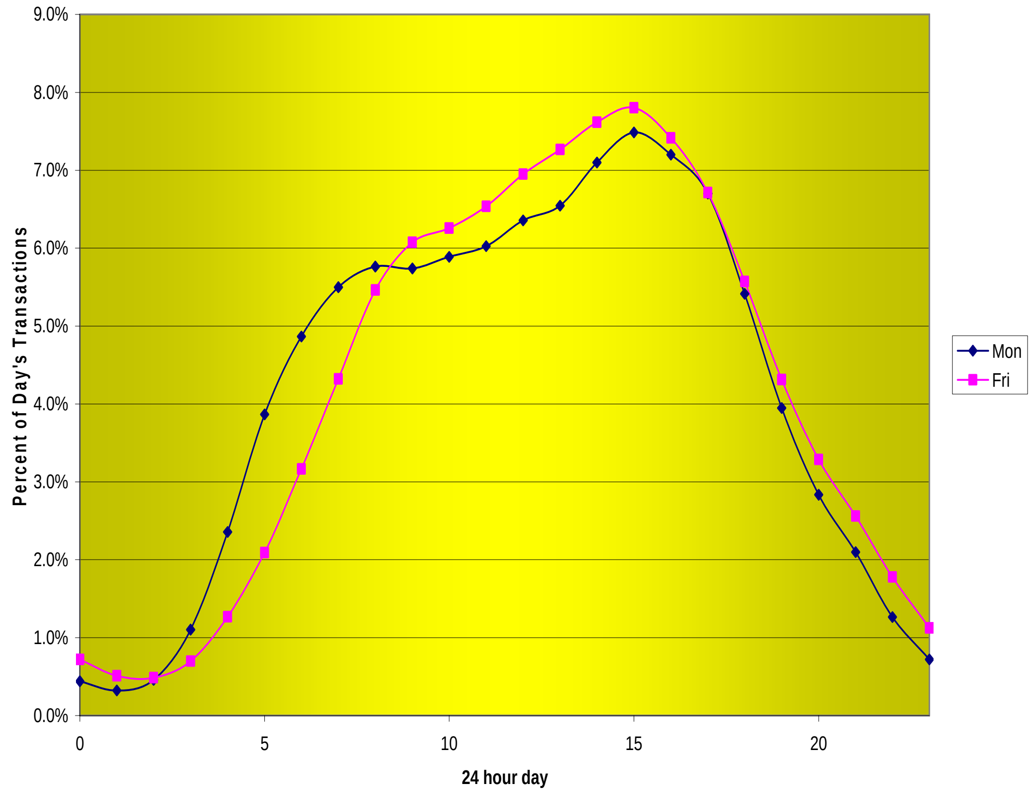
Analysis of Market Demand and Supply Variations

- 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

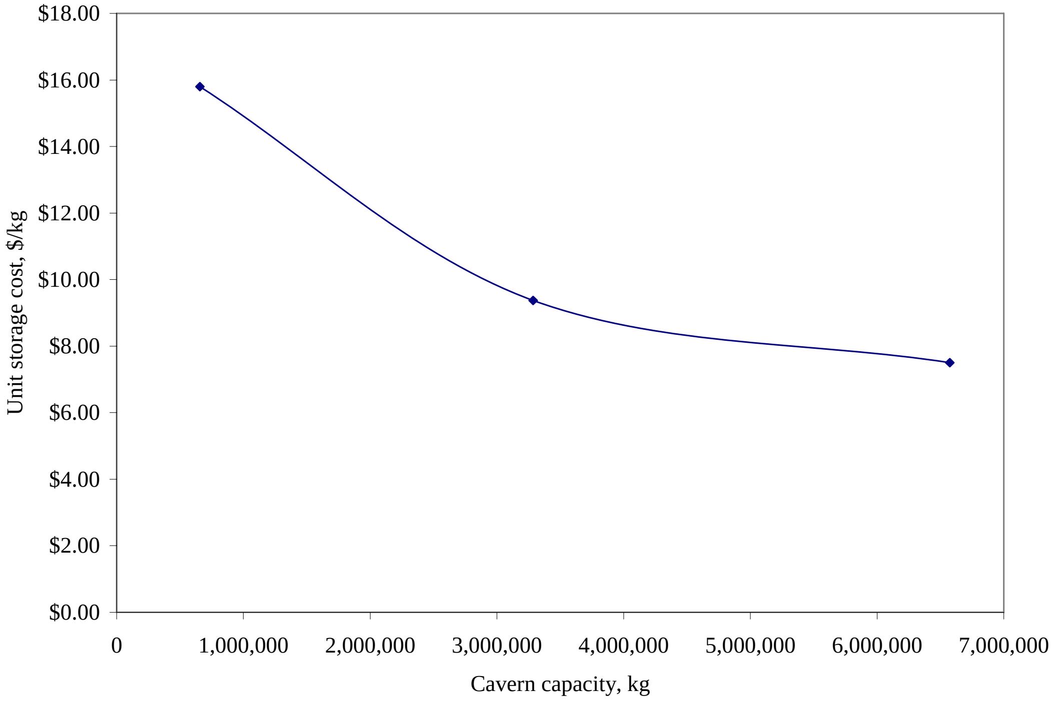
- Storage Problem
  - Production plants operate at constant rate, but demand varies
- Storage Options
  - Geologic gas storage
    - Low cost for very large amounts of hydrogen
    - May not be conveniently located
  - Liquefaction and liquid storage: Second best for large quantities
  - GH2 Tanks: Highest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

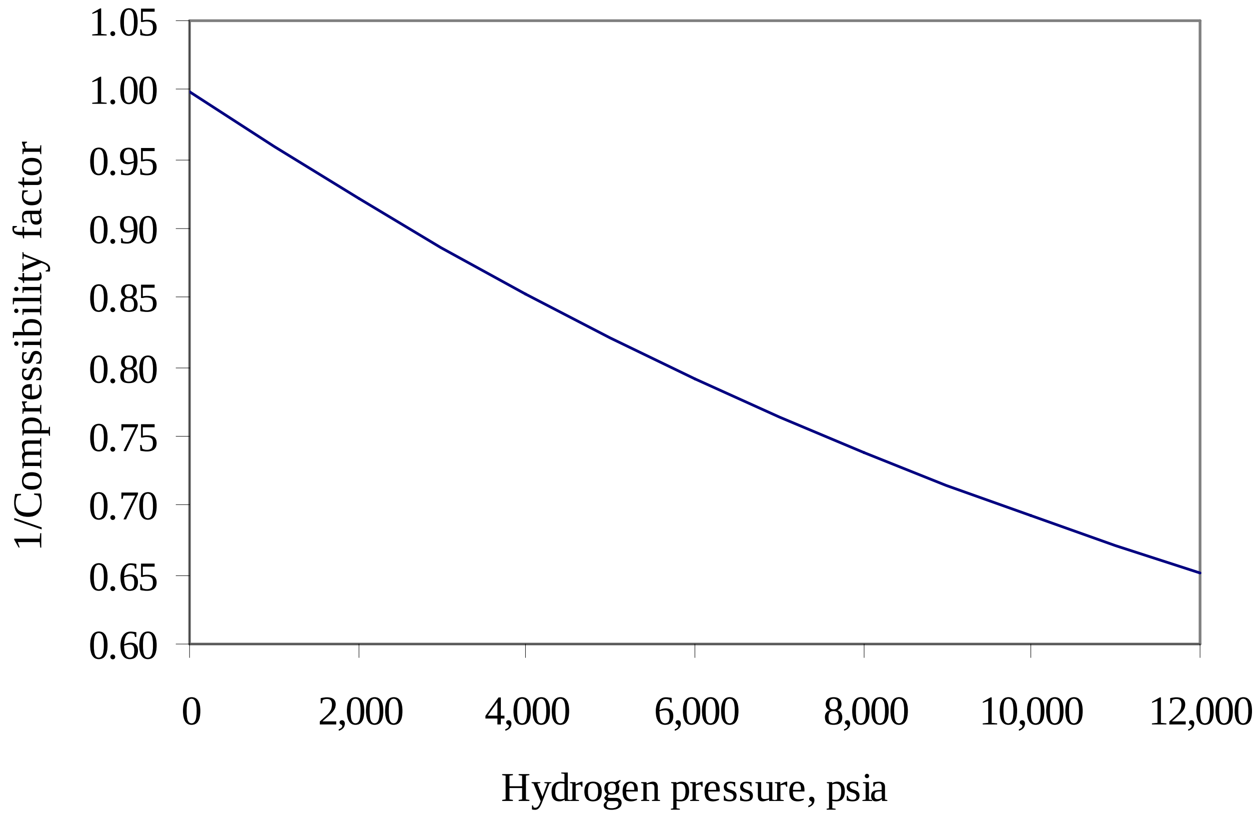
Low Pressure Gas Storage

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

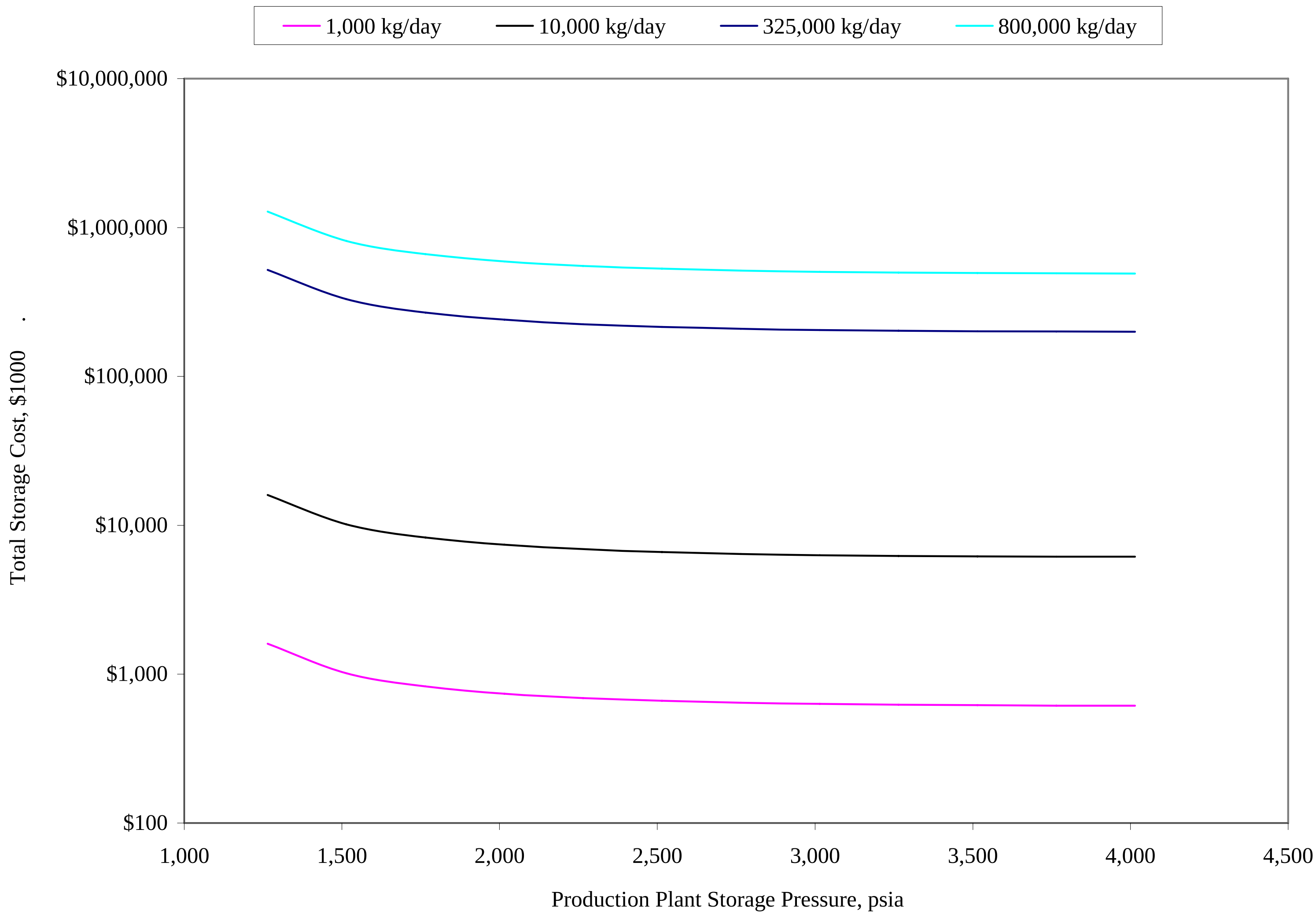
Low Pressure Gas Storage - Continued

- High strength, low alloy steels are preferred
- Low storage pressures are preferred



Low Pressure Gas Storage - Continued

Capital and operating cost versus pressure



Low Pressure Gas 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

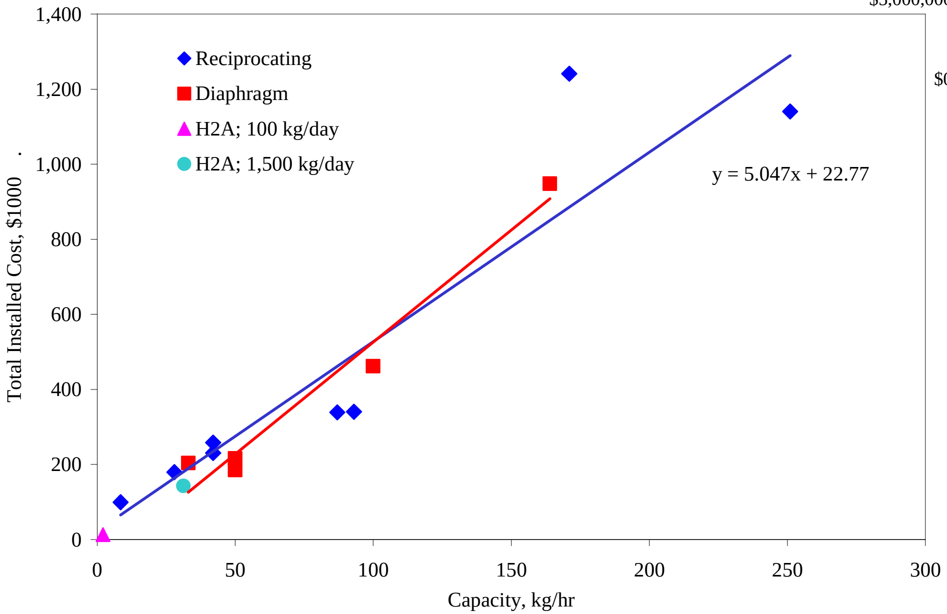
- $926/kg for vessel assembles, delivered
- $268/kg for storage auxiliaries
- $266/kg for engineering, site preparation, contingency, and permit fees
- <u>$1,460/kg of hydrogen stored</u> total investment cost

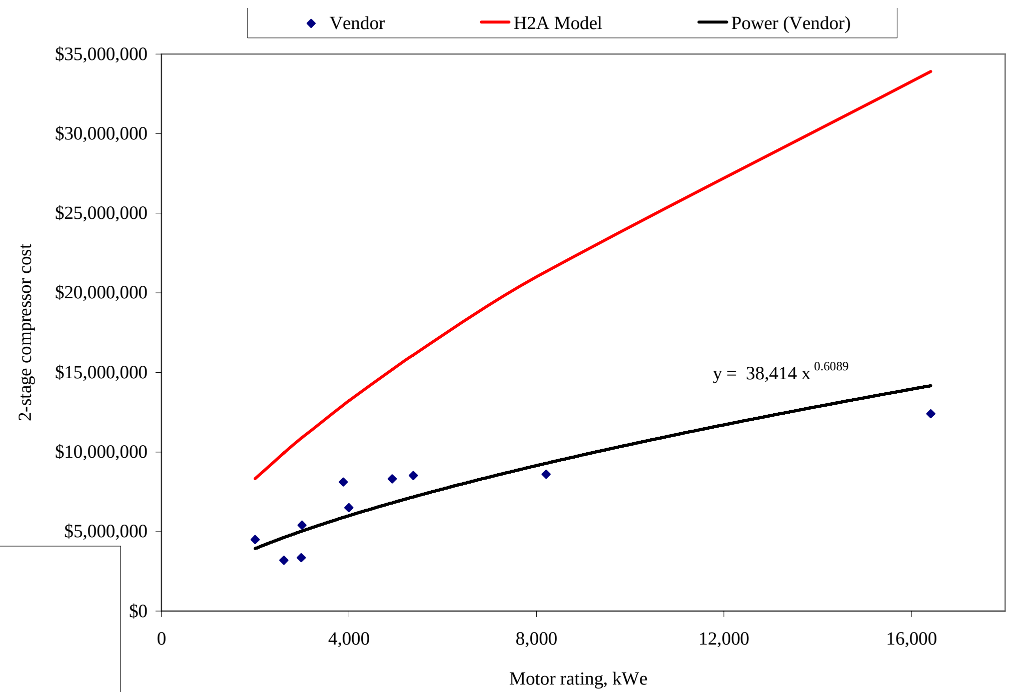
Designed for vehicle dispensing:
Only ~30% effective for storage

Compressor Costs for Storage and Dispensing

Large reciprocating and refueling site compressors

Small Compressors: Data from Rix, Greenfield, Knox-Western, Hydro-Pac, PDC Machines, PPI, and Hofer





Large Compressors: Data from Neuman & Esser, Burckhardt, Ariel, and Dresser-Rand

Large Hydrogen Compressors

Recommended inputs to H2A model

- H2A equation for electric power demand
- 88 percent isentropic efficiency
- Motor rating is 110 percent of power demand
- Largest commercial machine is 16,000 kWe
- 3-stage compressor costs are 120 percent of 2-stage costs
- Non-lubricated compressor power demand is 110 percent of lubricated compressor demand