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2012 DOE Hydrogen Program Review

Hydrogen Delivery Infrastructure Analysis

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Overview

Timeline

- Start: FY 2007
- End: Project continuation is determined annually by DOE

Budget

- 100% DOE funding
- FY11: $350 k
- FY12: $325 k

Barriers/Challenges

- Lack of analysis of H2 infrastructure options and tradeoffs
- Cost and efficiency of delivery components
- Lack of appropriate models and tools/stove-piped analytical capability

Partners

- Argonne National Lab
- Pacific Northwest National Lab
- National Renewable Energy Lab

Relevance

- ❑ Provide platform for comparing alternative component, and system options to reduce cost of hydrogen delivery
  - ✓ Identify cost drivers of current technologies for hydrogen delivery to early market applications of fuel cells
  - ✓ Identify and evaluate benefits of synergies between hydrogen delivery options to various markets (e.g., forklift market, FCV market)
  - ✓ Evaluate role of high-pressure tube-trailers in reducing refueling station capital
  - ✓ Evaluate the potential of novel delivery concepts for future market scenarios
- ❑ Assist in FCT program planning
  - ✓ Investigate delivery pathways with potential to achieve cost goals in MYPP
  - ✓ Help with defining future funding priorities to achieve targeted performance and cost goals
- ❑ Support existing DOE-sponsored tools (e.g., H2A Components, H2A production, MSM, JOBS FC, GREET)
  - ✓ Collaborate with model developers and lab partners
  - ✓ Collaborate with industry for input and review

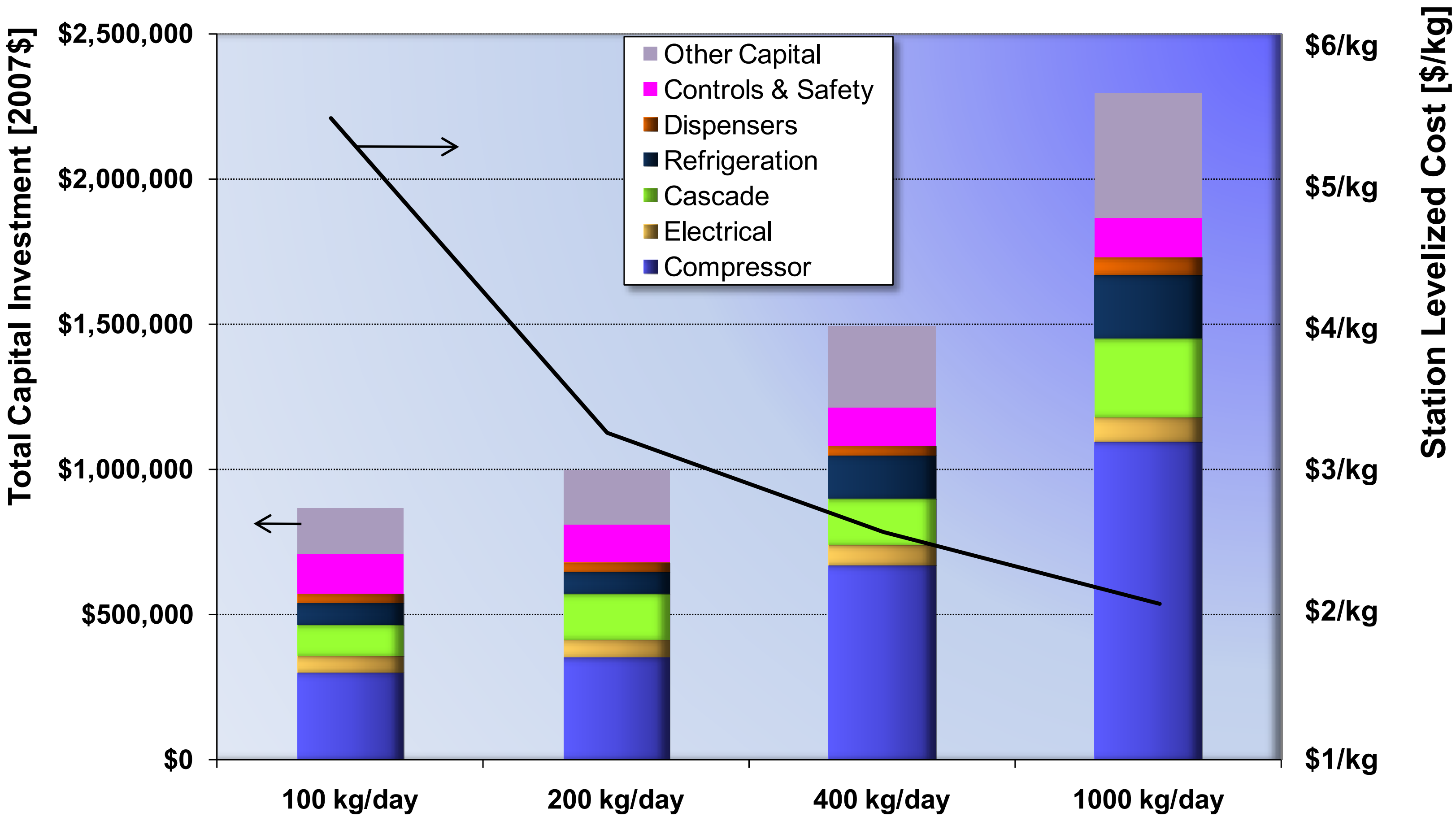
Approach

- Create **transparent, flexible, user-friendly, spreadsheet-based tool (HDSAM)** to examine new technology and options for hydrogen delivery
- Provide modeling structure to automatically link and size components into **optimized pathways** to satisfy requirements of market scenarios, and compute component and **system** costs, energy and GHG emissions
- **Collaborate** to acquire/review input assumptions, analyze delivery and dispensing options, and review results
- Provide **thorough QA**
  - Internally via partners
  - Externally, via briefings to Tech Teams, early releases to DOE researchers, industry interaction

MOTIVATION FOR ANALYSIS

(problem definition for early markets)

Early markets require high refueling station investment

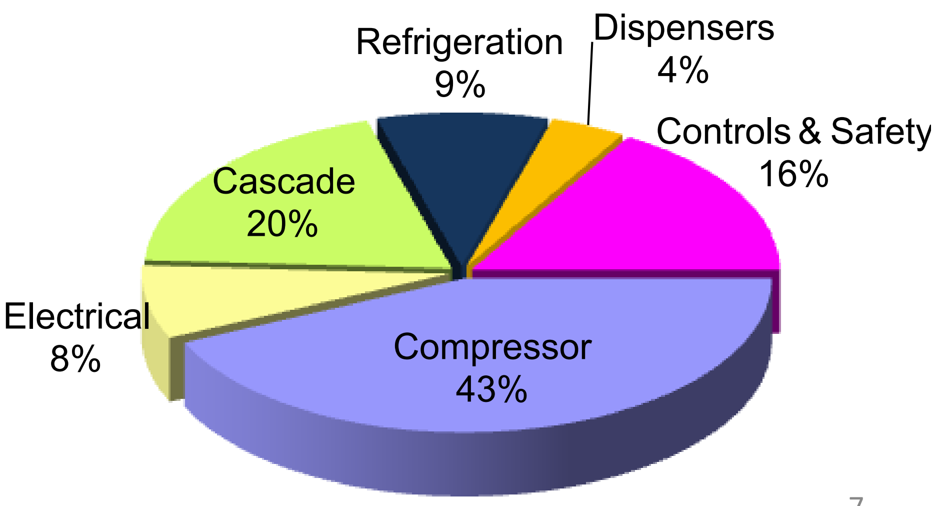


- Underutilization of the capital in early markets compounds the problem
- The problem is further compounded by the high investment risk (10%→30% IRR doubles the station cost contribution)

Investment strategies for early markets must deal with capital underutilization

Move the capital of the major components (i.e., packaging components) to upstream of the refueling station where:

- The capital has better utilization (serves multiple markets)
- The capital benefits from economies of scale
- The risk is distributed between different market segments and applications

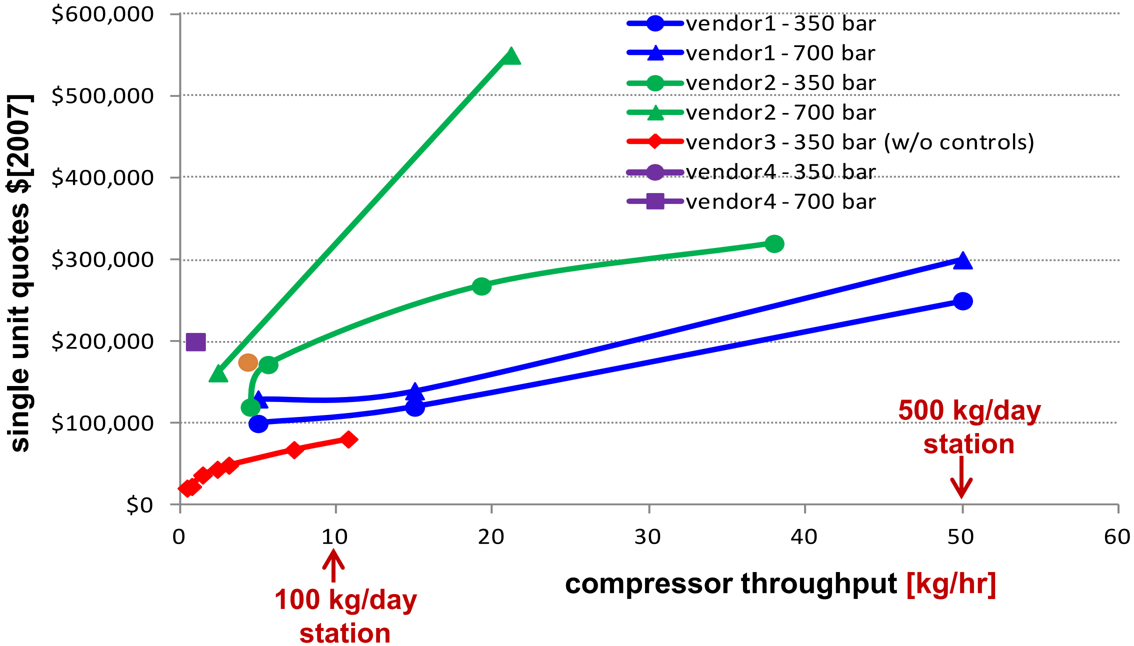


FY2012 Accomplishments

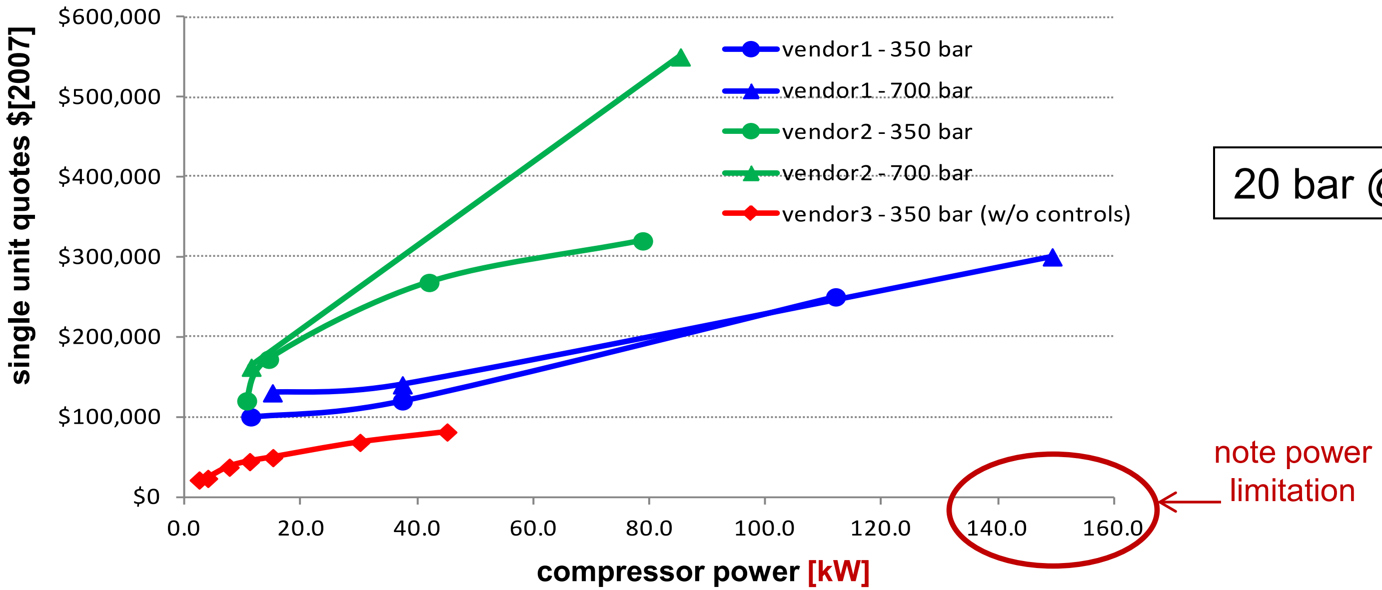
Month/Year	Milestone
October 2011	Developed three versions of HDSAM to assess 2005 and 2010 status of technologies, and define cost targets for 2020
November 2011	Evaluate current compression technologies
January 2012	Evaluate different configurations of high pressure tube-trailers and their viability for hydrogen delivery to early markets
March 2012	Develop demand parameters and examine cost of hydrogen refueling for forklift markets
May 2012	Evaluate role of high-pressure tube-trailers in reducing refueling station capital investment
July 2012	Examine impact of liquid hydrogen carriers on delivery and refueling station cost
September 2012	Document and publish analysis and supporting models

CURRENT COMPRESSION TECHNOLOGIES

Capital cost of station compressor varies with throughput and power

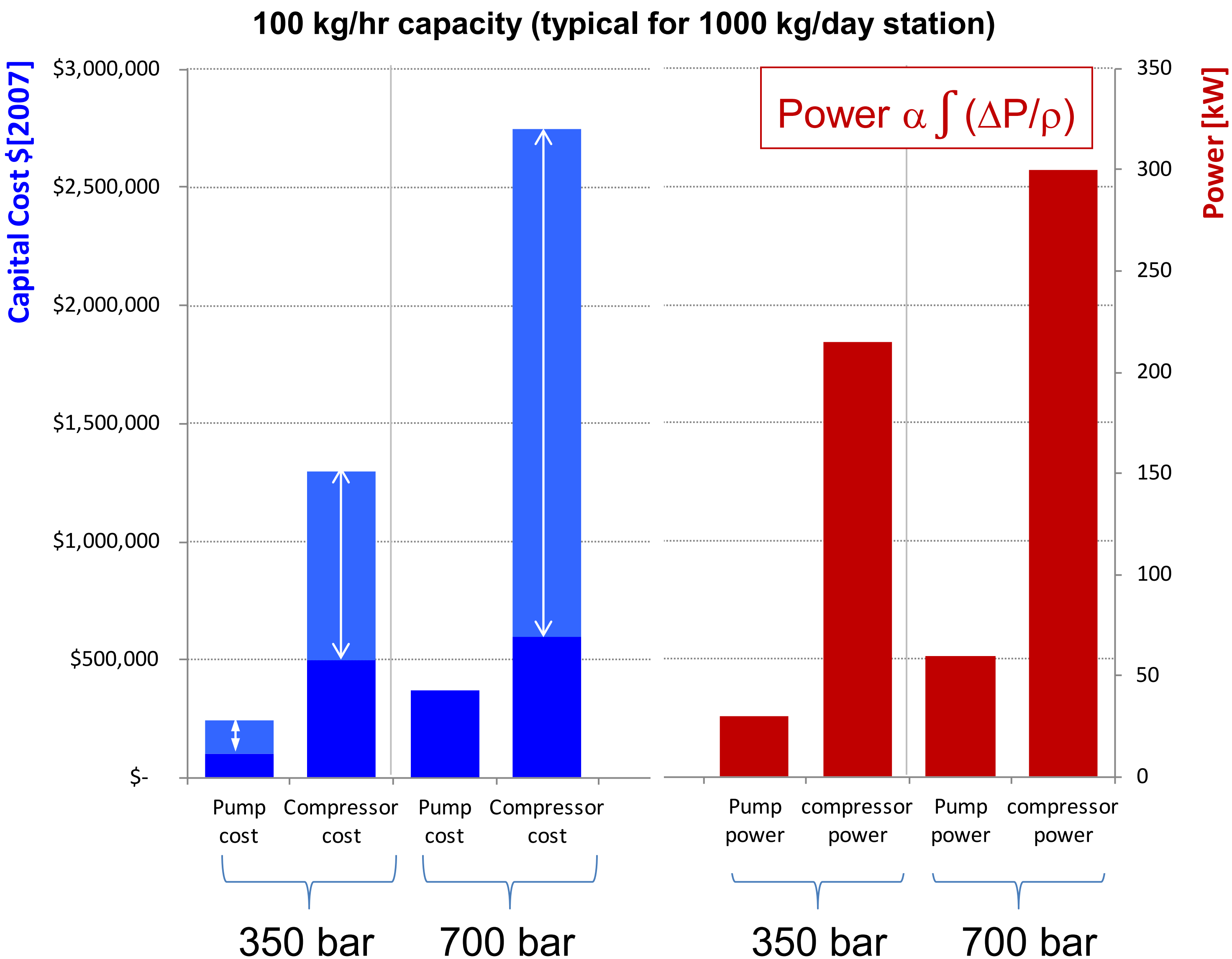


20 bar @ inlet



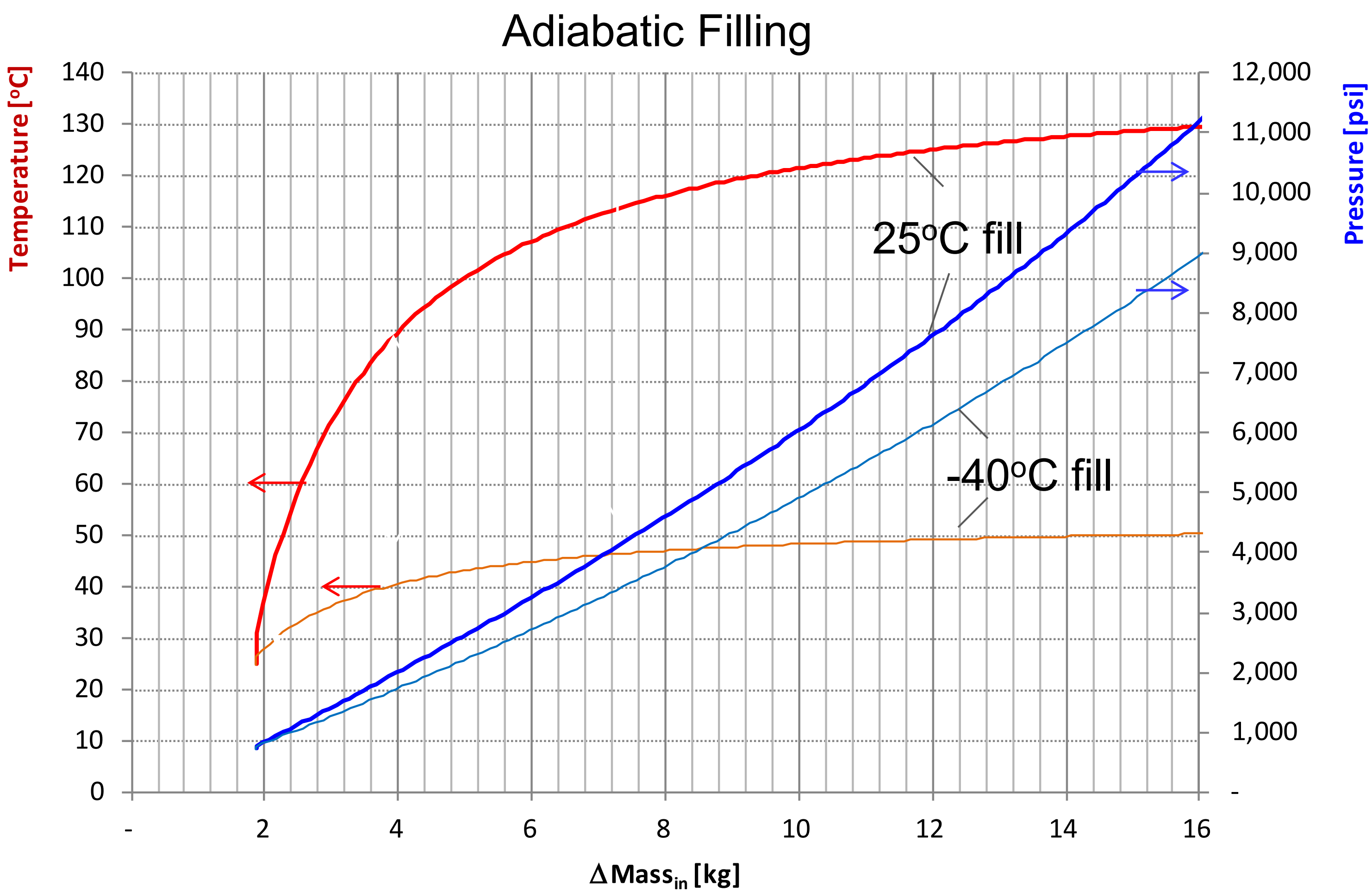
20 bar @ inlet

Compressors are more costly with greater variability and power requirements than pumps



Hydrogen compression poses additional challenges

- In addition to high capital and power requirements, fast fills will result in significant heat build up → cooling may be needed



In summary: compression at refueling station poses four major challenges

1. High compression capital cost per unit of hydrogen throughput
2. Underutilization of the compression capital in early markets
3. High compression power demand (electrical upgrades)
4. Limited fill rate unless significant cooling is provided

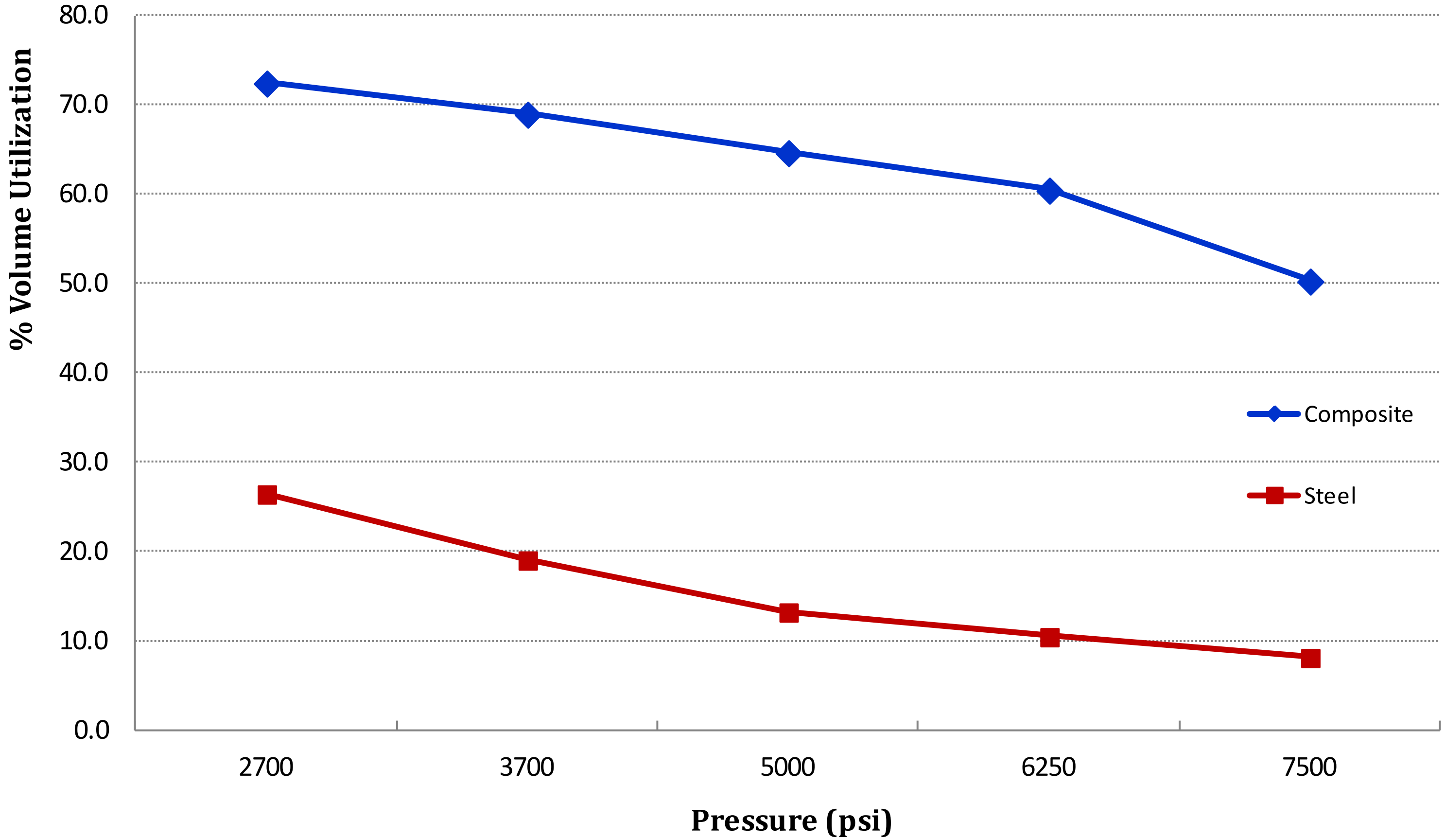
HIGH PRESSURE TUBE-TRAILERS

Tube-trailer configurations impact capacity and cost

- Evaluated cost implications of different tube trailer configurations:
  - ✓ Fill pressure (wall thickness)
  - ✓ Tube diameter
  - ➢ Number of tubes
  - ➢ Tube material (i.e., steel vs. composite)

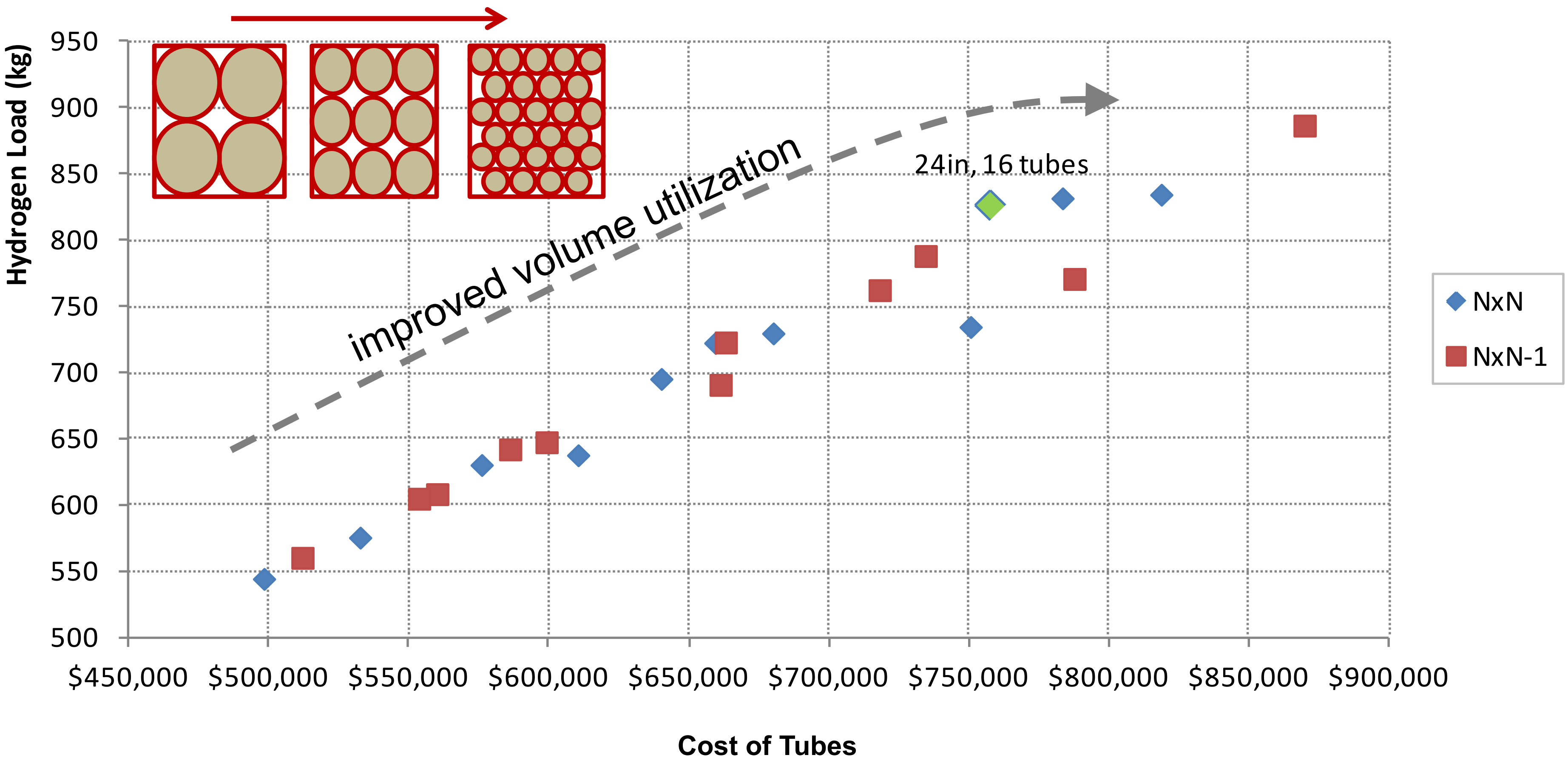
- Considering the following constraints:
  - ➢ Use ISO container (8’ x 8’ x 40’)
  - ➢ Weight limit of 80,000 lbs, height limit 13.5’
  - ➢ Empty trailer + Cab weight ~ 30,000 lbs
  - ➢ Material properties
  - ➢ ASME pressure vessel codes

Higher pressure results in lower volume utilization



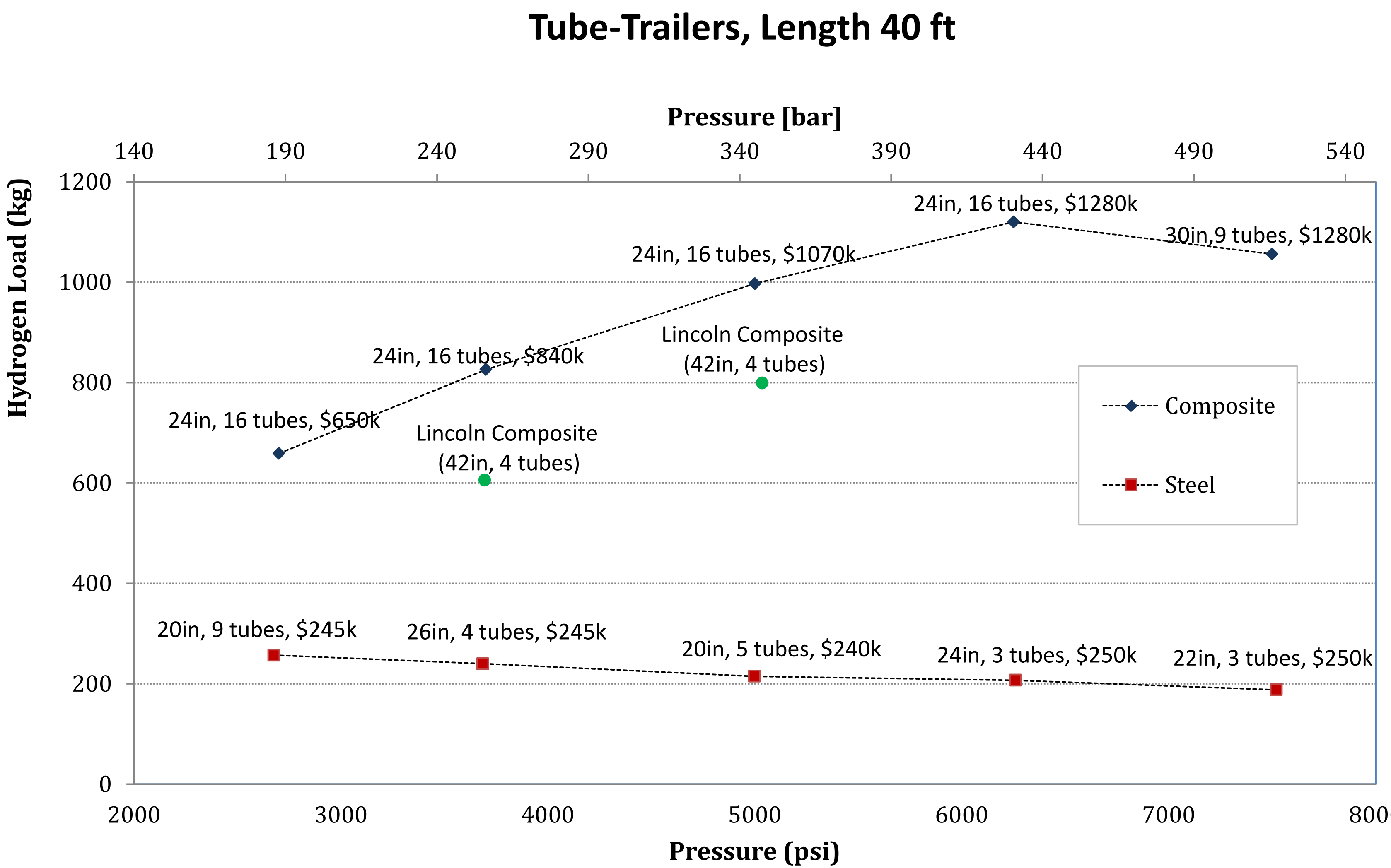
Cost of tubes increases with hydrogen load at given pressure

- Example shown for 3600 psi (250 bar) in composite tubes



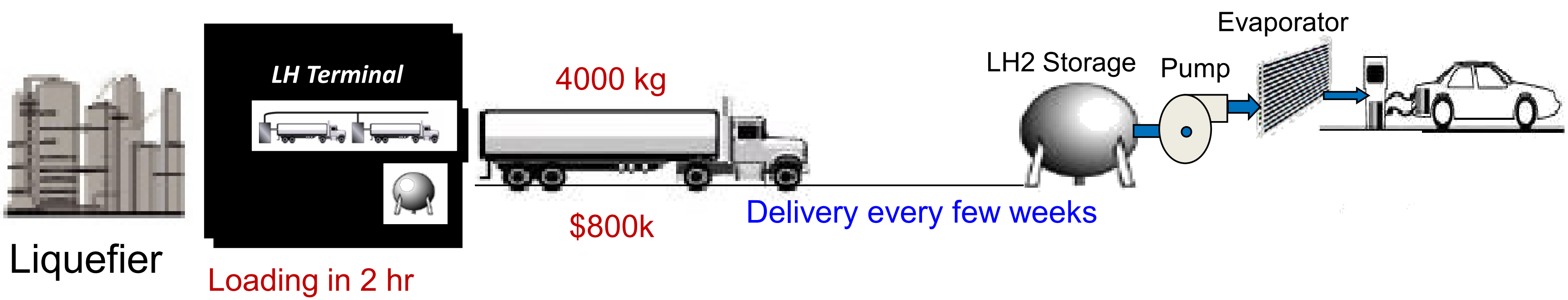
- Near linear increase in cost with H2 load, but up to a limit

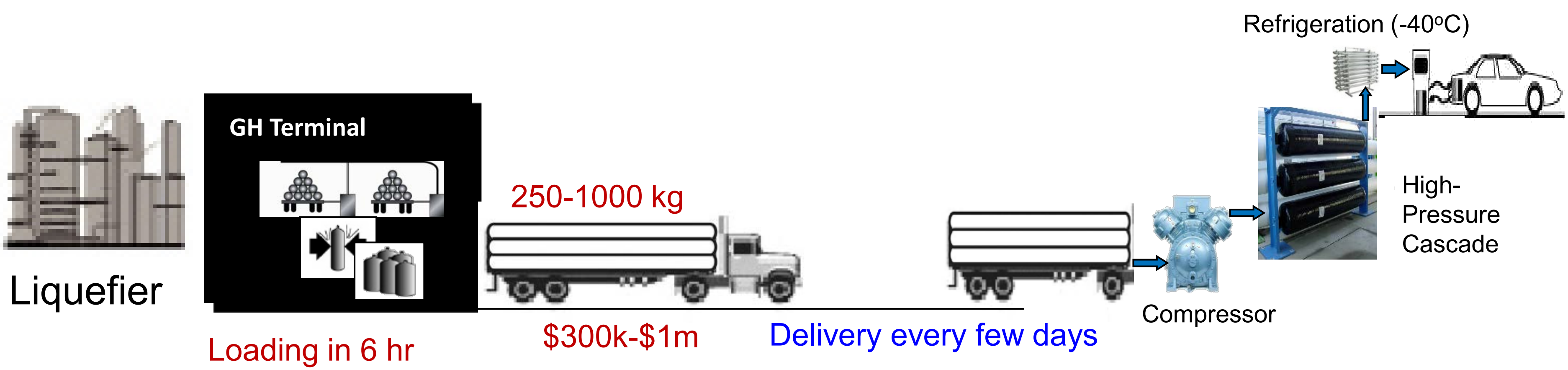
High-pressure tube-trailers require light-weight material (to stay below 50,000 lbs)



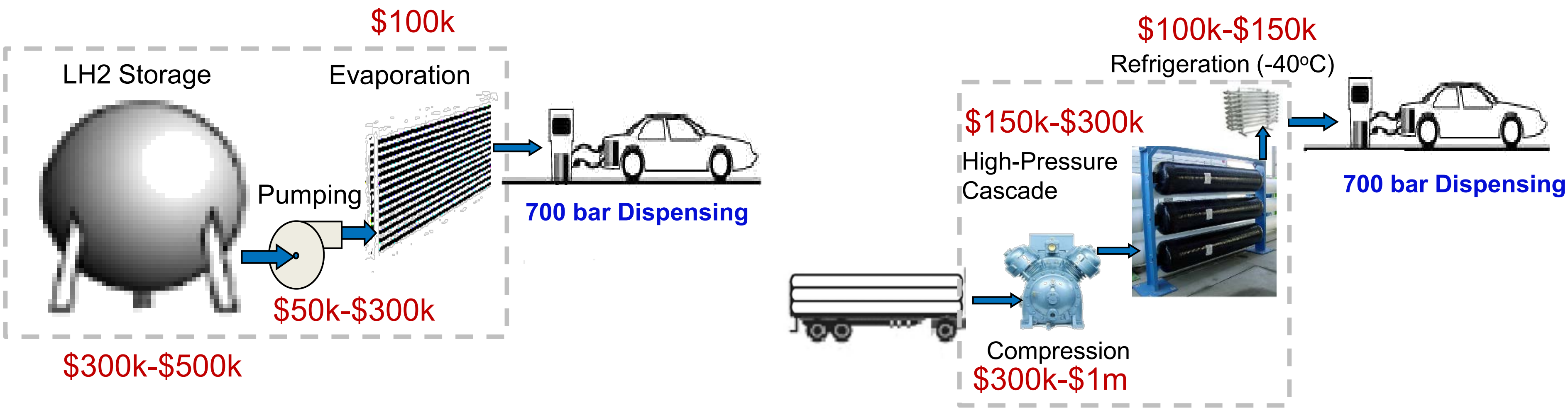
HYDROGEN TRUCKING OPTIONS

Pipeline delivery is not a likely option for the demand levels in early markets





Liquid delivery has advantages over gaseous delivery



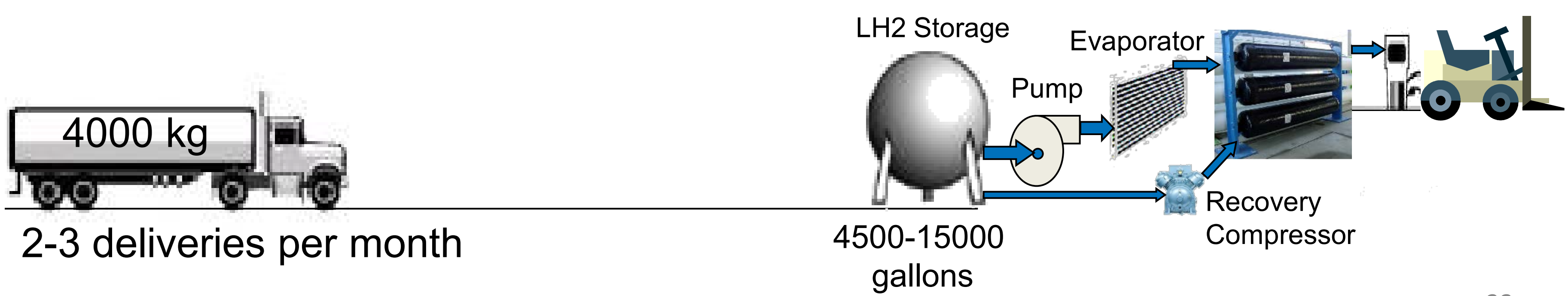
	LH2	GH2
Station capital investment	More favorable (with sizable demand)	Less favorable (high compressor/cascade capital)
GHG emissions	Less favorable (**high liquefaction GHG**)	More favorable
Delivery logistics	More favorable	Less favorable
Other issues	Boiloff rate	Cooling to -40°C
	Can benefit from surplus liquefaction capacity	Tube trailers eliminate need for onsite storage

HYDROGEN REFUELING FORKLIFT MARKETS

Forklifts refueling demand reflects operating parameters

Operational Parameters	Class I/II	Class III
On-board storage	1.5 kg	0.8 kg
On-board fill pressure	350 bar	350 bar
Fuel consumption	0.3 kg/h_{op}	0.05 kg/h_{op}
Refueling time	2 min	1 min
Hours of operation per shift	6	6

- ➢ Number of forklifts from each class
- ➢ Number of shifts per day
- ✓ Calculate daily demand of hydrogen and size refueling equipment



Forklift refueling cost estimates suggest opportunities and constraints

	150 kg/day	300 kg/day
Total installed capital	**$850k**	**$1.3m**
Other Capital (including site preparation)	**$200k**	**$400k**
Cost contribution of refueling	**$2.5/kg$_{H2}$**	**$2/kg$_{H2}$**
Monthly Lease of installed equipment (recover investment in 7 years)	**$15,000**	**$20,000**
Monthly Lease of installed equipment (recover investment in 10 years)	**$10,000**	**$15,000**

<u>What we have learned</u>:

- Hydrogen is available and can be delivered at a cost of ~$6/kg
- Current technology prefers the handling of volume deliveries in liquid form
- Business case exists for demand volumes > 150 kg/day
- Desired delivery frequency ~ 2-3 deliveries/month
- Lease of the installed equipment is a preferred option
- Some redundancy is built in to hedge against delivery disruption

Forklifts and FCVs have different refueling needs

	Forklifts	FCVs
Incumbent technology	**Battery**	**Gasoline ICE**
Operation range per fill	**4-6 hr**	**350-400 mi**
Fill pressure	**350 bar**	**700 bar**
Fill rate	**~1 kg/min**	**1.67 kg/min (cooling required)**
Demand profile	**Fairly flat**	**High peak/average ratio**
Utilization of capital	**High (similar to fleet operation)**	**Low in early markets**

- High-pressure tube-trailers can play an important role in reducing refueling stations capital investment and improve utilization in early FCV markets

Future Work

- Evaluate advanced compression technologies and novel compression concepts
  - Liquid ionic compressors, thermal compressors, electrochemical compression
- Examine issues related to liquid delivery options
  - Boiloff rates, venting vs. recovery, liquefaction energy and GHG emissions
- Evaluate storage technology options and new concepts
  - e.g., pre-stressed steel/concrete composite tanks for bulk storage
- Evaluate impact of chemical storage options
  - on delivery cost and refueling cost

Project Summary

- **Relevance:** Provide platform to evaluate hydrogen delivery (in $, energy and GHG emissions), estimate impact of alternative conditioning, distribution, storage and refueling options; incorporate advanced options as data become available; assist Hydrogen Program in target setting.
- **Approach:** Develop models of hydrogen delivery components and systems to quantify costs and analyze alternative technologies and operating strategies.
- **Collaborations**: Active partnership among ANL, PNNL and NREL, plus regular interaction with Fuel Pathways and Delivery Tech Teams, DOE researchers and industry analysts.
- **Technical accomplishments and progress:**
  - Evaluated current compression technologies
  - Evaluated configurations high pressure tube-trailers
  - Developed demand and cost estimates of hydrogen refueling in forklift markets
  - Evaluating role of high-pressure tube-trailers in reducing refueling station capital investment
- **Future Research**: Examine new concepts and technology options for refueling station cost reduction (advanced compression and storage, and carrier options), revise/update data, and respond to Tech Team recommendations.

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