2008 DOE Hydrogen Program Review

Hydrogen Delivery Infrastructure Analysis

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Project PD 15 Kelly
Project PD 16 Mintz

Overview

Timeline

- Nexant et al.
  - Start: June 2005
  - End: September 2008
  - Percent complete: 95%
- Argonne et al.
  - Start: October 2006
  - End: Continuous

Budget

- 100% DOE funding
- Nexant et al. $1,886,504
  - FY05-07
- Argonne et al.
  - FY07 $380,000
  - FY08 $460,000

Barriers

- Lack of H2/carrier infrastructure options analysis
- Cost of delivery components

Partners

- Nexant et al. (PD 15)
  - Nexant
  - TIAX, LLC
  - Chevron
  - Air Liquide, GTI, Pinnacle West
- Argonne et al. (PD 16)
  - Argonne National Lab
  - National Renewable Energy Lab
  - Pacific Northwest National Lab

Project Objectives

- Refine technical and cost data in H2A Delivery Models (H2A Hydrogen Delivery Components Model and H2A Hydrogen Delivery Scenario Analysis Model, HDSAM) by incorporating industry inputs and evolving technologies
  A. Revised data and analyses
  B. Enhanced model capabilities (optimization) and user options
  C. Improved consideration of storage and component sizing
  D. Carrier analyses
- Explore options to reduce hydrogen delivery cost, including storage optimization and novel carriers
- Develop enhanced models to assist in program planning and development

Approach

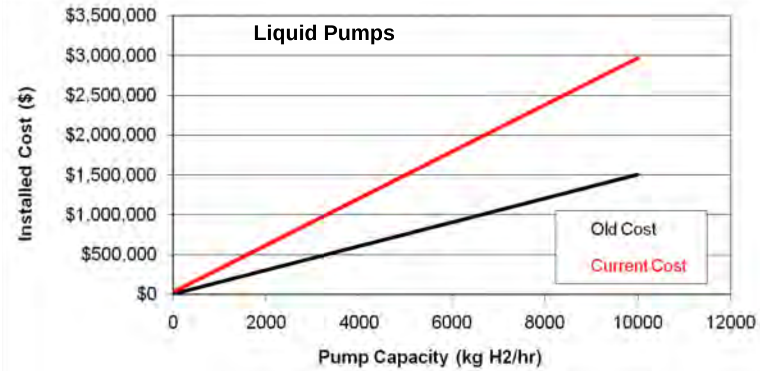
- **Collaborate** to analyze storage, forecourt and packaging/conditioning options and incorporate findings in H2A Delivery Models
  - Analyze storage, compression, liquid handling, fuel station options and costs (Nexant et al.)
  - Complete a first-phase screening of materials and pathways to identify viable carrier options and create H2A-like tools to consistently evaluate them (TIAX)
- Create **transparent, flexible, spreadsheet-based tools** to examine new technologies, operating targets, packaging options, and produce **"snap shots" of delivery cost** resulting from input assumptions. **Not transition models,** but used in transition modeling
  - Delivery Components Model: cost contribution of individual components (NREL)
  - Delivery Scenarios Analysis Model: cost contribution, energy and greenhouse gas emissions of entire pathways (ANL)
    - **User-friendly interface** to quickly and easily define scenarios (ANL)
    - Structure to automatically link and size components into **optimized pathways** to satisfy demand requirements of scenario and compute **system delivery** cost (ANL, Nexant, NREL)
- Provide **thorough QA** of H2A Delivery Models
  - Internally via partners (PNNL)
  - Externally, via briefings to Tech Teams, early releases to EERE researchers

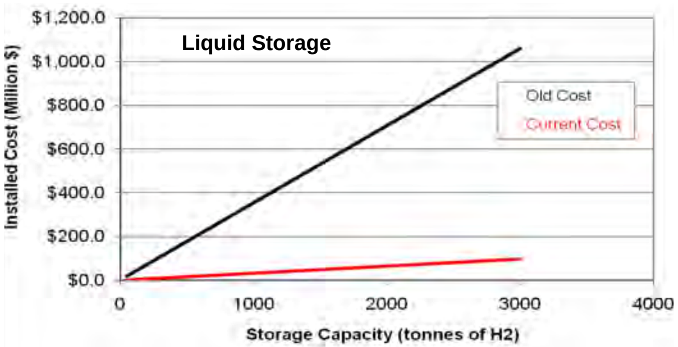
FY08 Accomplishments

Month/Year	Milestone
December 2007	Draft Version 2.0 of Hydrogen Delivery Components Model and Hydrogen Delivery Scenario Analysis Model (H2A Delivery Models)
March 2008	Beta testing and external review of H2A Delivery Models
May 2008	Posting Version 2.0 of H2A Delivery Models on EERE website
June 2008	Draft report documenting Nexant analyses and changes to H2A Delivery Models
August 2008	Posting final Nexant report and Version 2.0 Users' Guides on EERE website

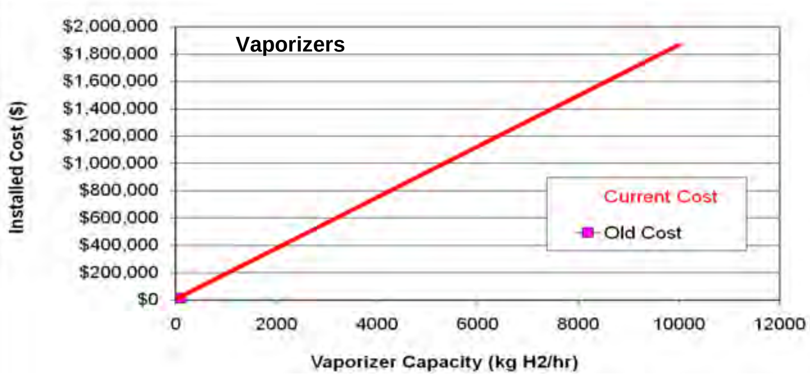
A. Nexant Developed Technical and Cost Data on Delivery Components to Expand and Update H2A Delivery Models

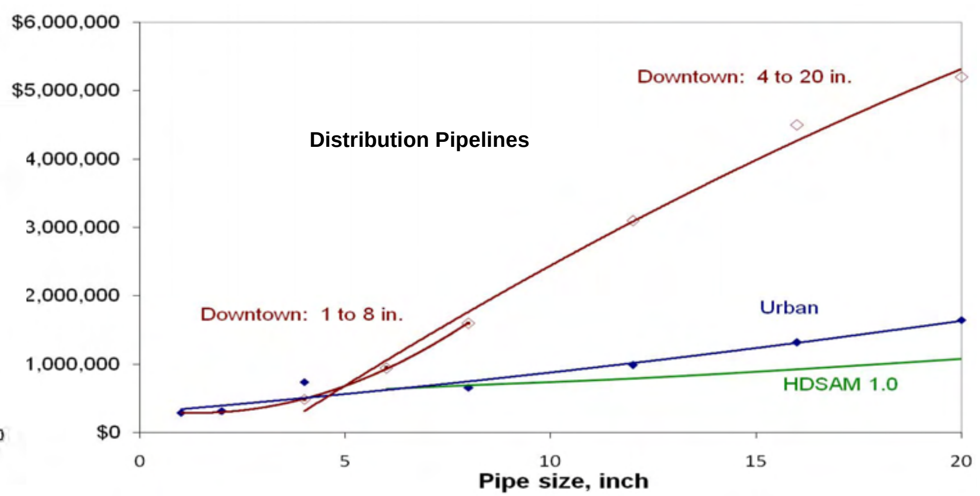
- Revised cost data and equations (liquid handling, pipelines, storage, labor, indirect capital, O&M, owners' costs) and installation factors
- Compressor, liquefaction and storage cost analyses
- Revised fuel demand profile



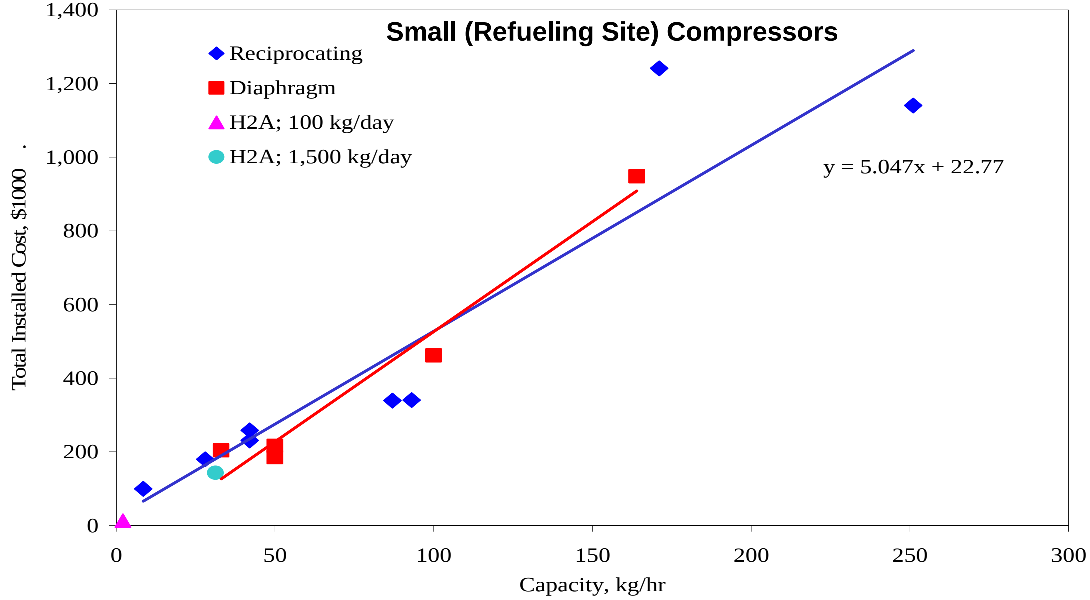


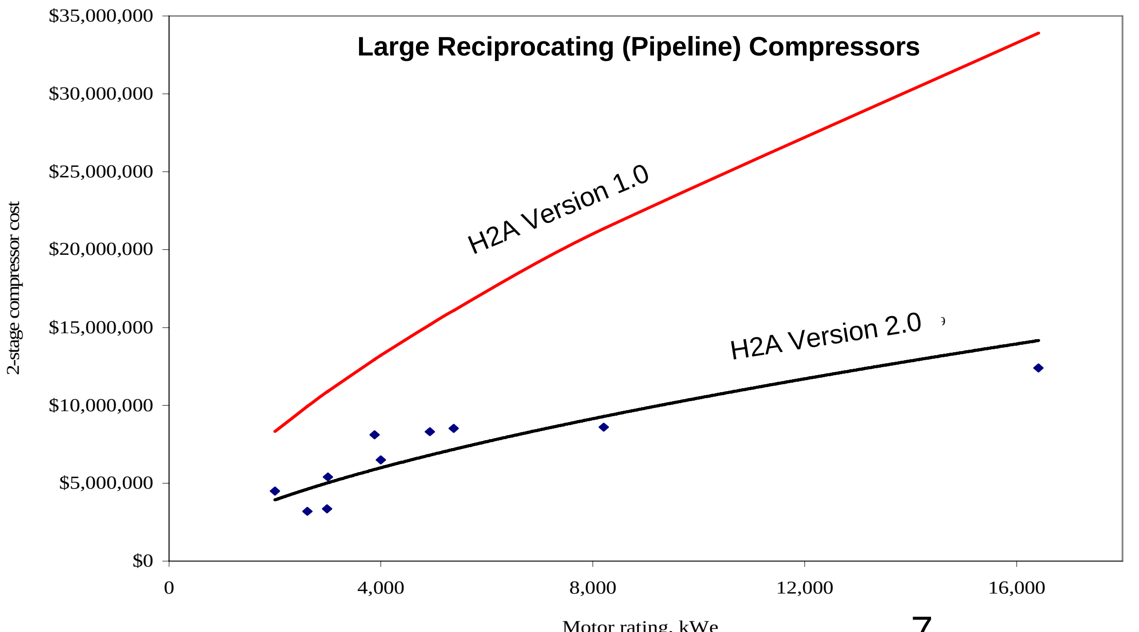
In Version 1.0 storage and vaporizer costs based on small, fuel-station-sized units





Small and Large Compressors Were Analyzed

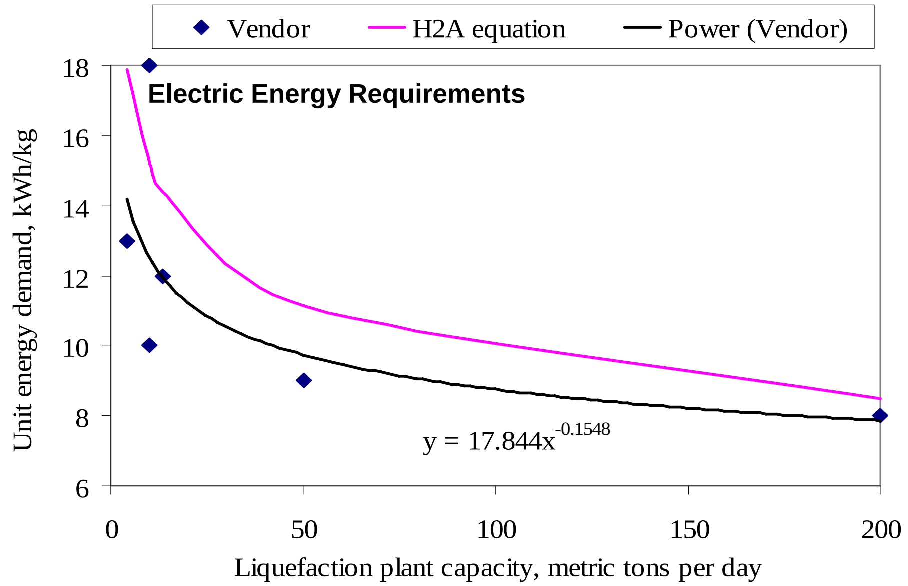


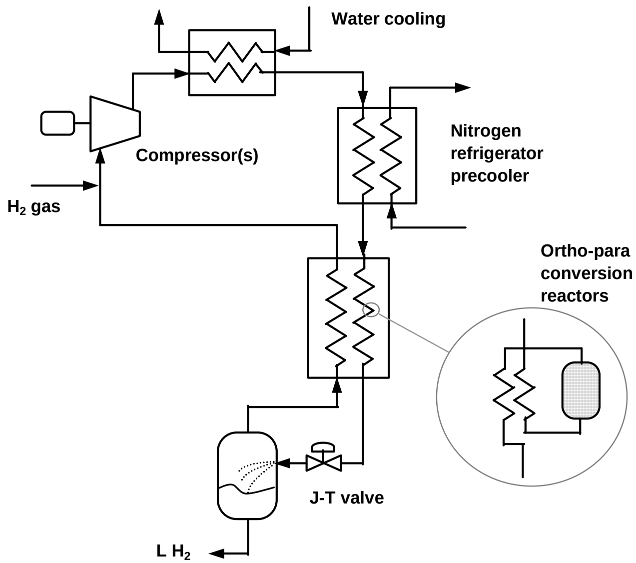


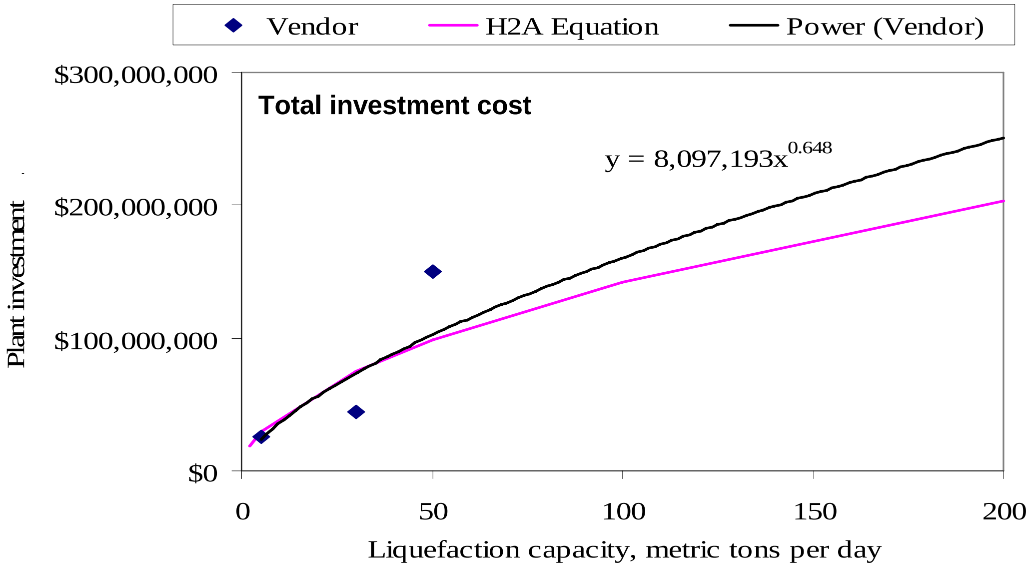
- **Quotes obtained from Rix, Greenfield, Knox-Western, Hydro-Pac, PDC Machines, PPI, and Hofer (small compressors); Neuman & Esser, Burckhardt, Ariel and Dresser-Rand (large compressors)**
- **88% isentropic efficiency**
- **Motor rating = 110% of power demand**
- **Largest commercial machine = 16,000kWe maximum size**
- **3-stage compressor costs = 120% of 2-stage costs**
- **Non-lubricated compressor power demand = 110% of lubricated design (also needs overhaul every 1-1.5 yrs, and costs more initially)**

Liquefaction Cost and Energy Demand Were Estimated

- **Basic process**
  - Compress
  - Cool to temperature with positive Joule-Thompson coefficient
  - Throttle to form liquid
- **Isentropic demand = 3.9 kWh/kg**
- **Unit size: 0 to 200 metric tons per day**
- **8 kWh/kg minimum energy consumption**
- **98.5% annual plant availability**
- **Indirect cost factors add 20% to total installed cost**



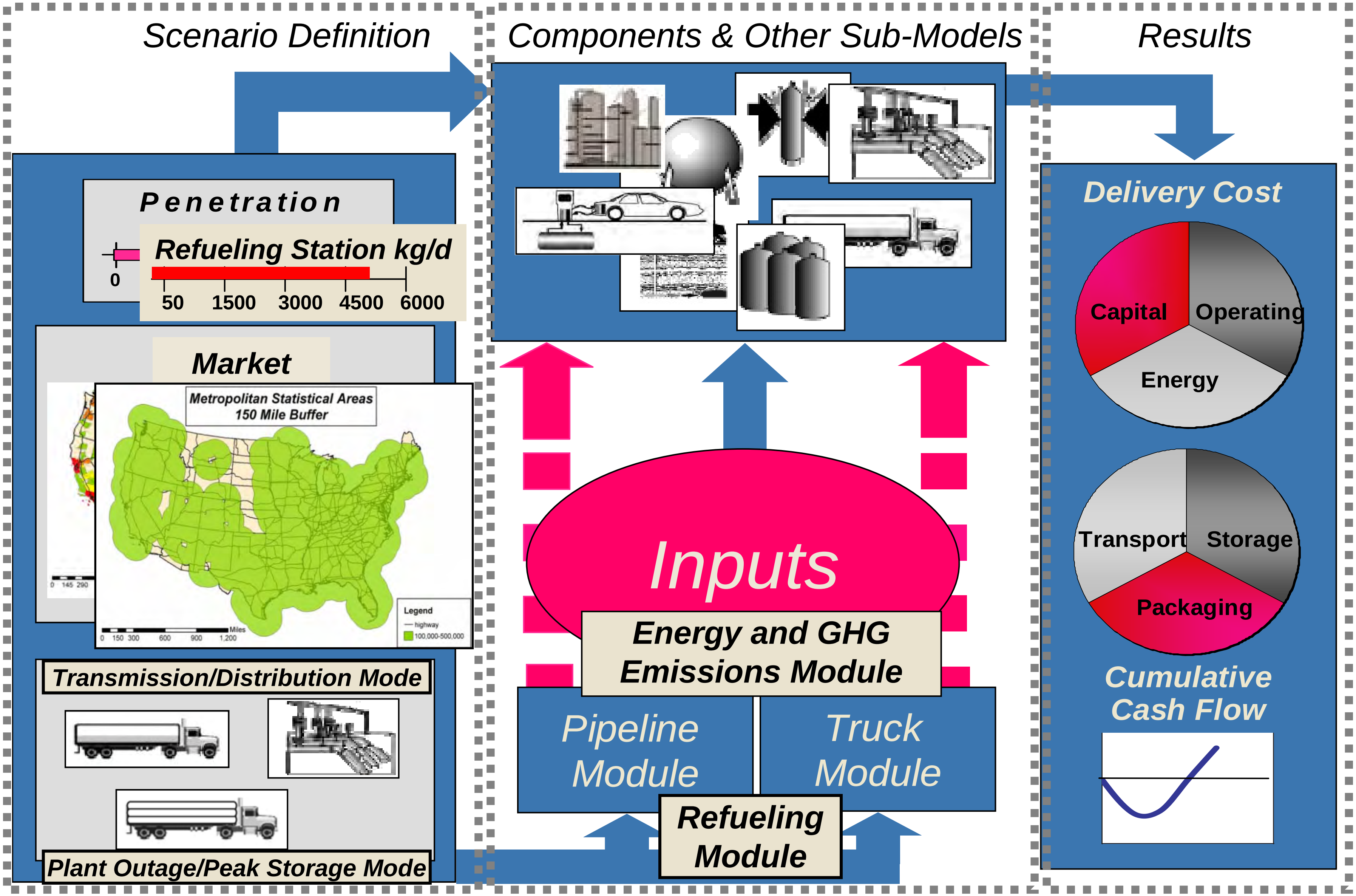




B. New H2A Delivery Models Have Enhanced Capabilities and User Options

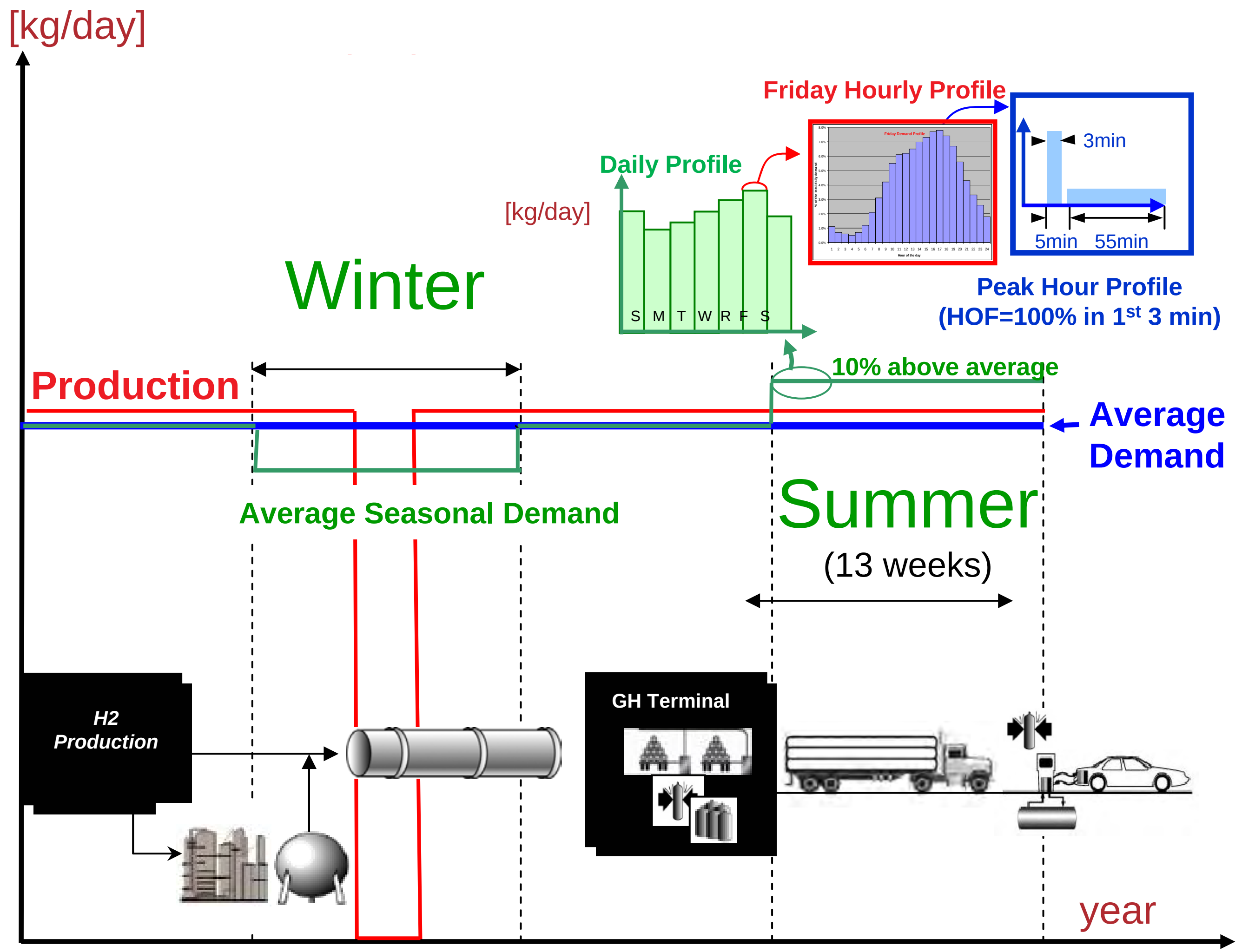
- Refueling station components (cascade vs. low-pressure storage, compressor/electrical requirements, evaporator/pump, boil-off recovery)
- Refueling station optimization (GH2 and LH2, based on total refueling station cost)
- Pipeline geometry (multiple main pipelines, separate downtown calculations)
- Practical limitation on component size (liquefier, compressor)
- Additional HDSAM user options (combined urban/intercity markets, alternative transmission/distribution modes, range of refueling station sizes, liquid or geologic storage for plant outages & peak demand, energy & CO_2 emissions)

Overview of HDSAM 2.0



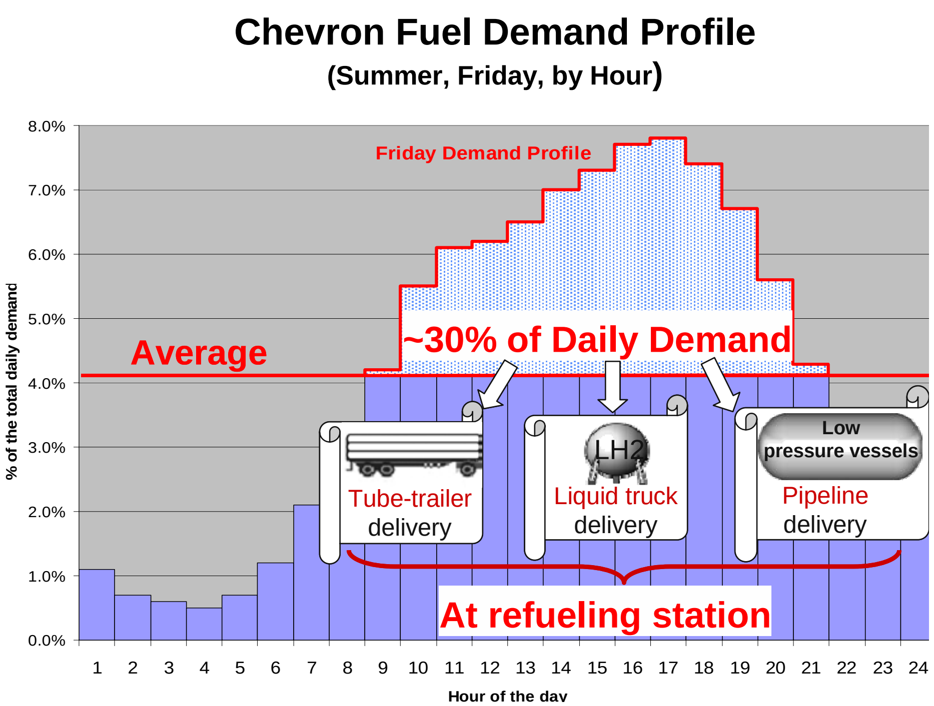
C. New H2A Delivery Models Use Storage to Accommodate Demand Peaks and Production Outages

- Components sized to meet Chevron fuel demand profile
- Pathway storage optimized for peak demand (late afternoon, Friday, summer, peak (HOF) hose occupied fraction)
- Variable capacity refueling stations (50 – 6000 kg/day)
- Additional pathways (mixed-mode transmission/distribution, liquid or geologic storage for production outage and summer peak)

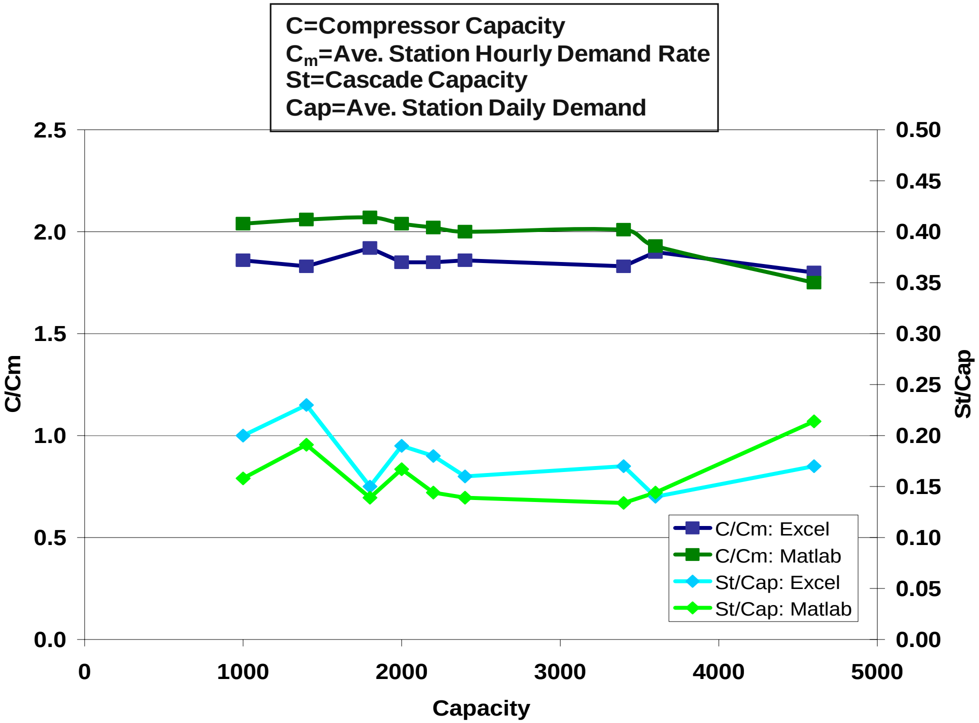


And a Fuel Demand Profile to Size Storage and Components at Refueling Stations and Upstream

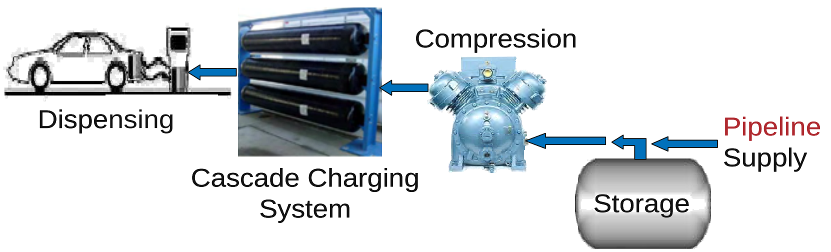
- Hourly supply to refueling station can meet peak demand if on-site storage satisfies difference between peak and average demand
  - Continuous supply (pipeline) requires a **minimum of 1/3 daily demand** in on-site storage
  - Truck supply requires a **minimum of 150% of daily demand**, not to exceed 2 deliveries/day in on-site storage
- Compressors, pumps-evaporators and cascade systems sized to peak demand
  - Avg hourly demand: ~4% daily demand
  - Peak demand: ~8% daily demand
- Upstream capacities ensure sufficient supply at each stage of pathway
  - Account for losses, compressor reliability
  - Replaces constant capacity factor in V1.0

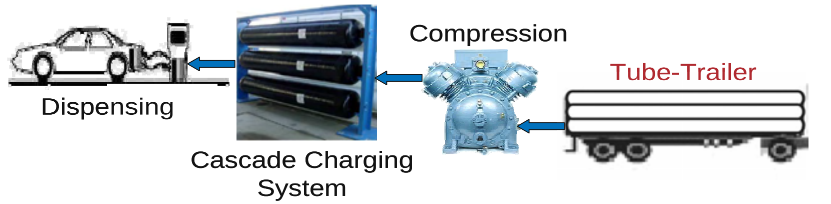


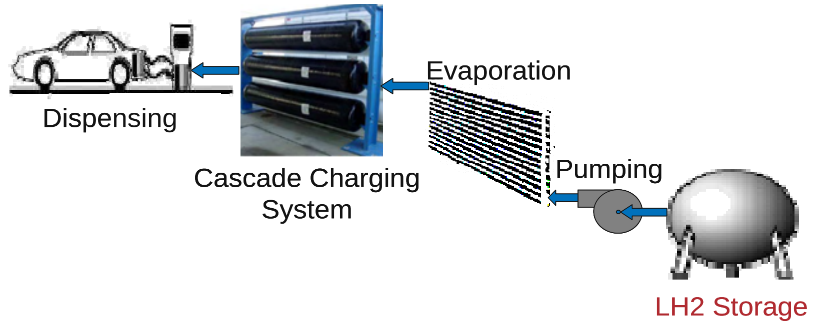
Model Iterates between Compressor/Pump and Cascade Costs to Estimate Optima for Given Station Size



Refueling Station Components







- Delivery model optimization **validated** using TIAX's Matlab-based model
- Compressor capacity**: ~2X average hourly demand** (estimated and independently validated)
- Cascade system capacity: **~15% average daily demand** (estimated and independently validated)

D. Analysis of Alternative Hydrogen Carriers* Potential to Meet DOE 2015 Goals

DOE Goals

On-Board Storage Parameters	2010 Goal	2015 Goal
Gravimetric Energy Density (kWh/kg)	2.0	3.0
System Weight Percent Hydrogen	6.0%	9.0%
Volumetric Energy Density (kWh/liter)	1.5	2.7

Conventional Storage Technology

On-Board Storage Parameters	cH2 (5,000 psi)	cH2 (10,000 psi)	Liquid H2
Gravimetric Energy Density (kWh/kg)	1.8	1.6	2.3
System Weight Percent Hydrogen	5.4%	4.8%	6.9%
Volumetric Energy Density (kWh/liter)	0.6	0.8	1.2

Novel Carrier Material Types and Delivery Characteristics

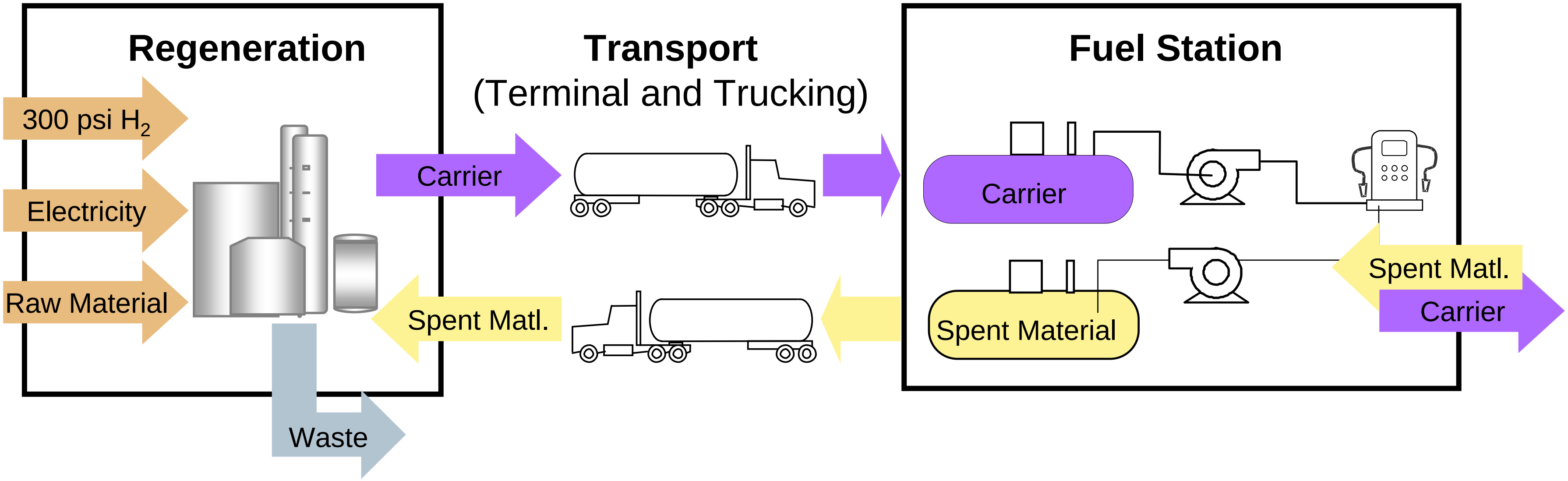
Material Type	Example Material	Storage State	H_2 Release
Metal Hydrides	Sodium Alanate	Packed Powder	Endothermic Desorption
Chemical Hydrides	Sodium Borohydride	Aqueous Solution	Catalyzed Exothermic Hydrolysis
Liquid-Phase Hydrogen Carrier	N-Ethylcarbazole	Liquid	Endothermic Dehydrogenation
High Surface Area Carbon Sorbents	AX-21	Low-Temp Solid Powder	Endothermic desorption

*** Defined as non-molecular H2 packaging or materials for storage/transport**

Carrier Options Are Combinations of Different Transport Modes, Material Types, Delivery Methods and Fueling

Transport Mode	Material Type and State (Packaging)	Delivery Method	H_2 Fueling
Truck Trailer: Liquid H2 Carrier	Liquid-Phase Hydrogen Carrier	Carrier Off-Load	Liquid Carrier
	Chemical Hydride Solution		Compressed Hydrogen
	Metal Hydride Slurry		
Truck Trailer: Solid H2 Carrier	Metal Hydride Powder	Trailer Drop-Off	Compressed Hydrogen
	Solid-State Carbon Sorbent	Hydrogen Off-Load	
Pipeline	Liquid-Phase Carrier	Pipeline-to-Liquid Storage	Liquid Carrier
	Chemical Hydride Solution		
	Metal Hydride Slurry	Pipeline-to-Dehydrogenation	Compressed Hydrogen

To Model Carrier Options, Delivery Methods Must Be Defined, Processes Characterized and Inputs Developed



- Major cost contributors: initial capital, energy continuous material
- Today's processes are likely to improve (e.g. less need to continuously replace spent material)

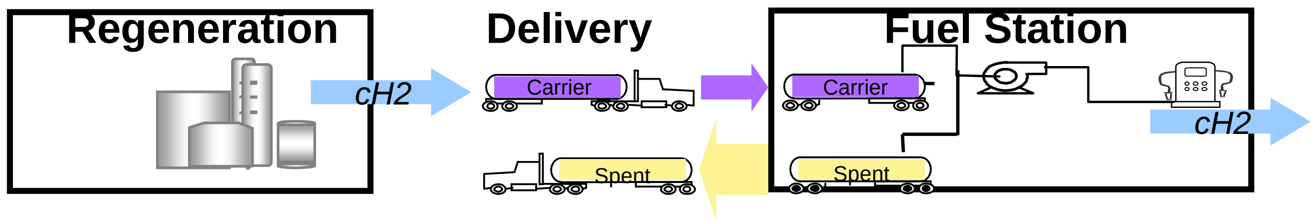
- Inputs: H2 yield, capital cost, total delivery time
- Transport of carrier and spent material in same truck
- Cost estimates of trailers and transfer equipment for powders must be improved

- Fueling station will dispense either the carrier (for onboard dehydrogenation) or cH2
- May include charged and spent material storage and equipment for discharging hydrogen from carrier (dehydrogenation reactor)
- Material properties (e.g., toxicity) may restrict use of carriers

Four CH2 Fueling Options Have Been Analyzed

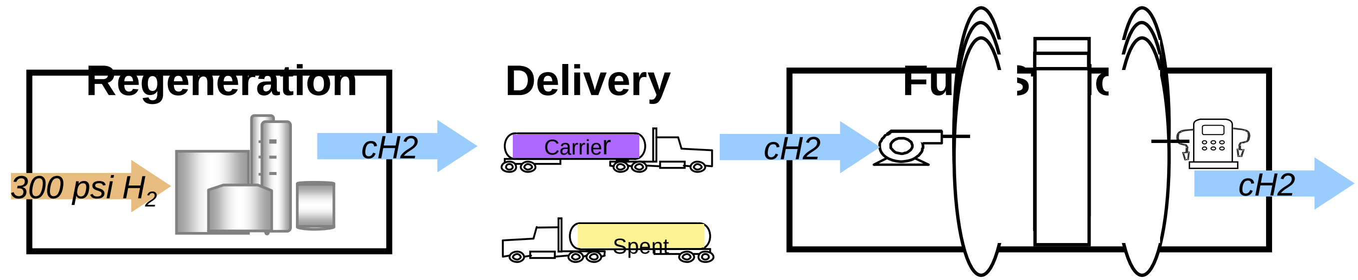
1. Trailer Drop-Off

(solid carrier)

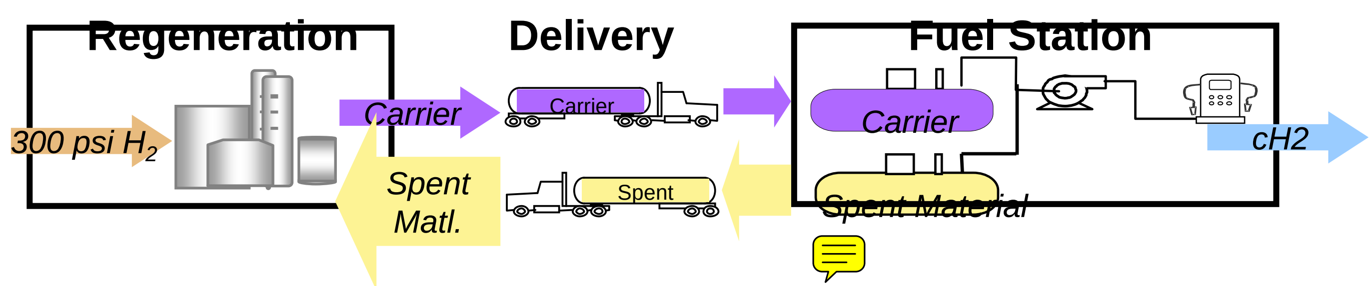


2. Hydrogen Off-Load

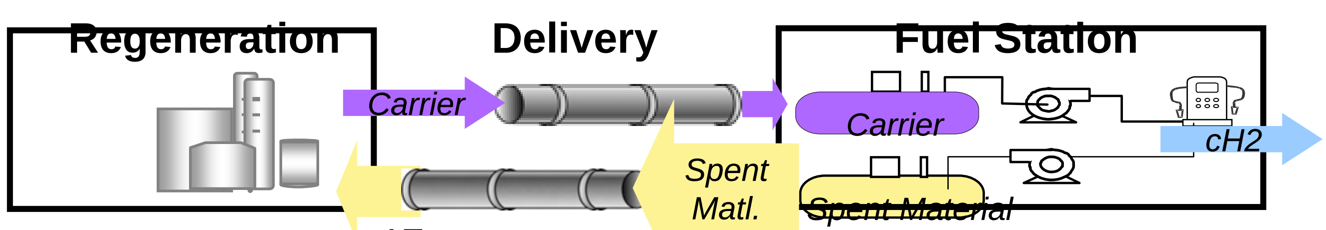
(solid carrier)



3. Carrier Off-Load
(liquid, slurry or
aqueous solution)



4. Pipeline
(liquid, slurry or
aqueous solution)



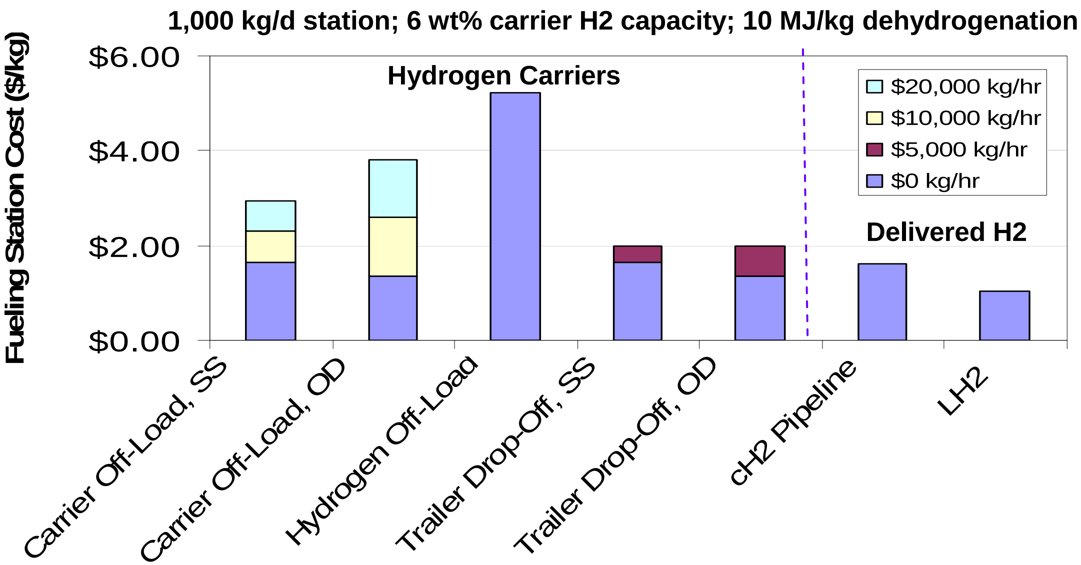
For Each Delivery Method, Fuel Station Components Were Evaluated with Expanded H2A Delivery Components Model

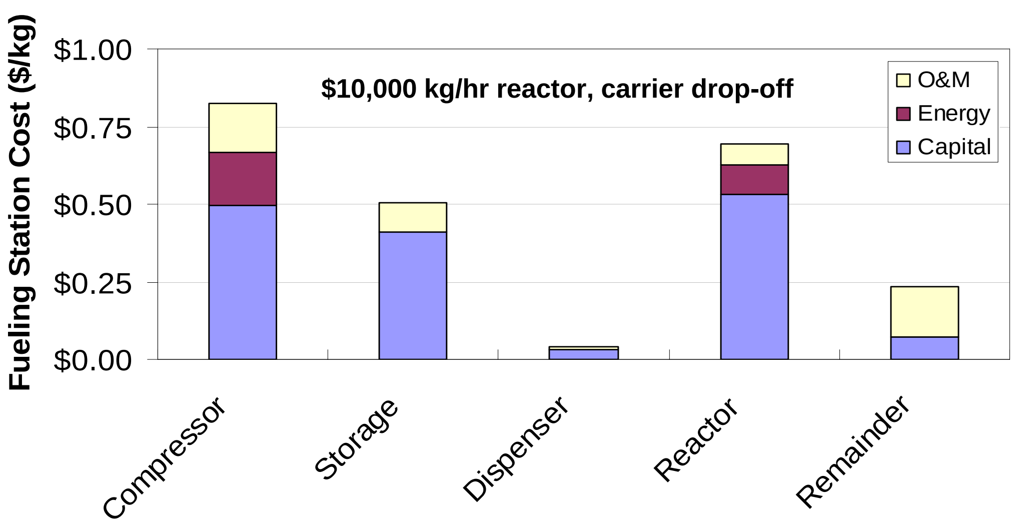
Delivery Method	Vehicle Fueling Method	Steady-State or On-Demand	Trailer Bay	Off-Load Comp.	Liquid Storage	Dehydrogenation Reactor	Low-P Storage	High-P Comp.	Cascade Storage	Dispenser Type
Liquid Carrier Off-Load	cH2	SS			Y	Y	Y	Y	Y	cH2
		OD			Y	Y		Y	Y	cH2
Liquid Carrier Drop-Off	Liquid Carrier	ND			Y					Liq
Solid Carrier H2 Off-Load	cH2	OD		Y		Y	Y	Y	Y	cH2
Solid Carrier Trailer Drop-Off	cH2	SS	Y			Y	Y	Y	Y	cH2
		OD	Y			Y		Y	Y	cH2
Pipeline	cH2	SS				Y	Y	Y	Y	cH2
		OD				Y		Y	Y	cH2
Pipeline	Liquid Carrier	ND			Y					Liq

SS = Steady-State Desorption ; OD = On-Demand Desorption ; ND = No Desorption Required

For CH2 Fueling, Station Cost Depends on Dehydrogenation Most Carrier Options Exceed Conventional Delivered H2

- Since **dehydrogenation reactor costs are uncertain,** fueling stations were evaluated at multiple cost points
- For 6 wt% carrier, dehydrogenation must be inexpensive to beat fuel station cost for conventional cH2 pipeline or LH2 delivery
- For a $10,000/(kg/hr) reactor and carrier drop-off, **capital costs** (compressor, storage, reactor) **dominate** (see figure)
- Pipeline delivery also dominated by capital cost (largely distribution lines to individual stations) and has similar compressor and cH2 storage cost (~$1.38/kg)
- Costs shown are for fuel stations only. **Pathway results will differ.**



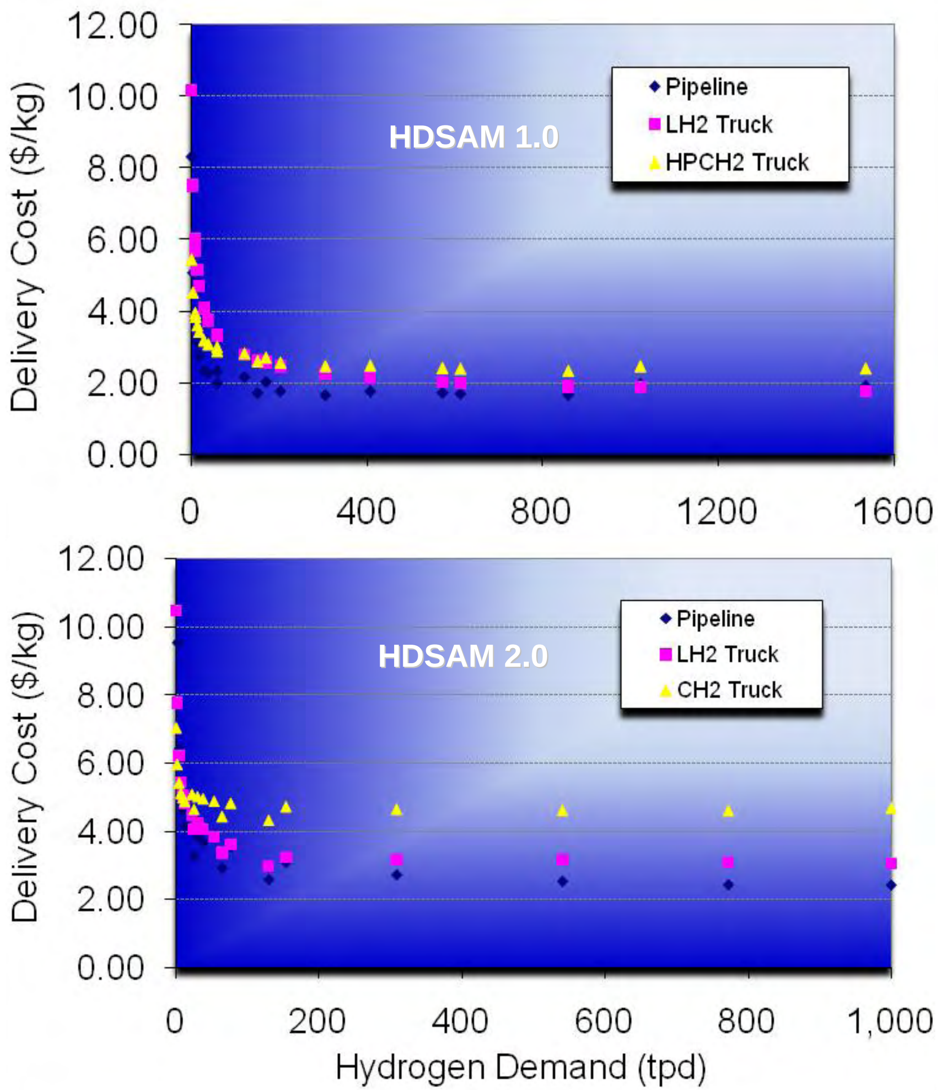


Conclusions and Next Steps in Hydrogen Carrier Analysis

- Alternative carriers have potential for improved storage density, but have yet to meet DOE goals
- Numerous trade-offs (i.e. trailer drop-off vs. H2 off-loading) necessitate **analyzing entire delivery pathways**
  - Component models have been developed for many portions (e.g., regeneration and trucking as well as fuel station)
- **Regeneration** requirements for most carriers require additional and more complex components than conventional H2 delivery methods
- Using a single carrier for delivery and on-board storage reduces the need for expensive hydrogen discharge equipment at the fuel station but moves the cost of H2 discharge onto the vehicle (those costs are not evaluated in this delivery analysis)
- Liquid carriers are most compatible for delivery and on-board storage
- Many liquid carriers (i.e. NaBH4 sol'n, MgH2 slurry) have complex **dehydriding** processes and equipment for which **costs are uncertain**
- Important to avoid making pathway decisions based on limitations of present technologies and materials. Unlike other options in H2A Delivery Models carriers are advanced technologies.

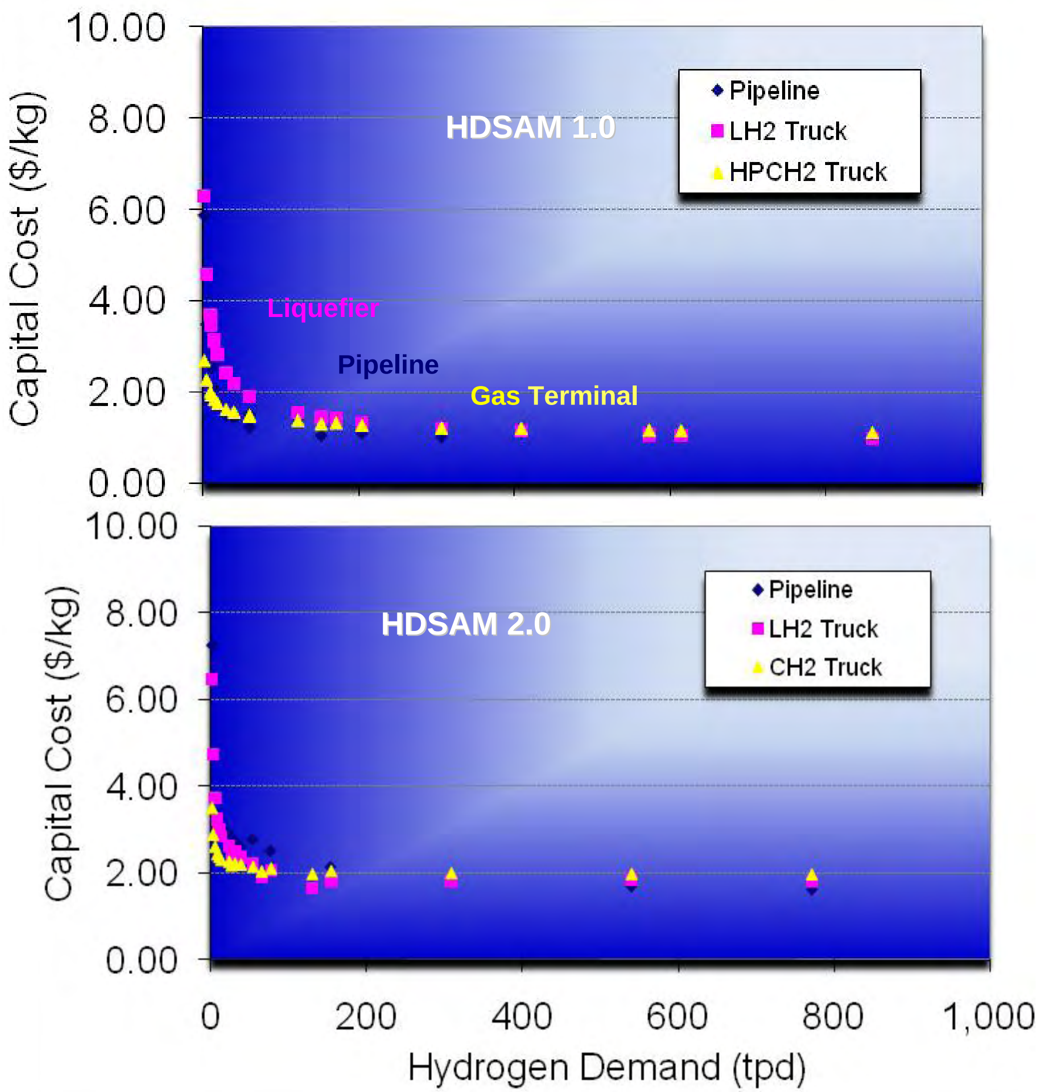
Hydrogen Delivery Models
Version 2.0 Versus Version 1.0

Most Delivery Costs Are Higher in HDSAM 2.0



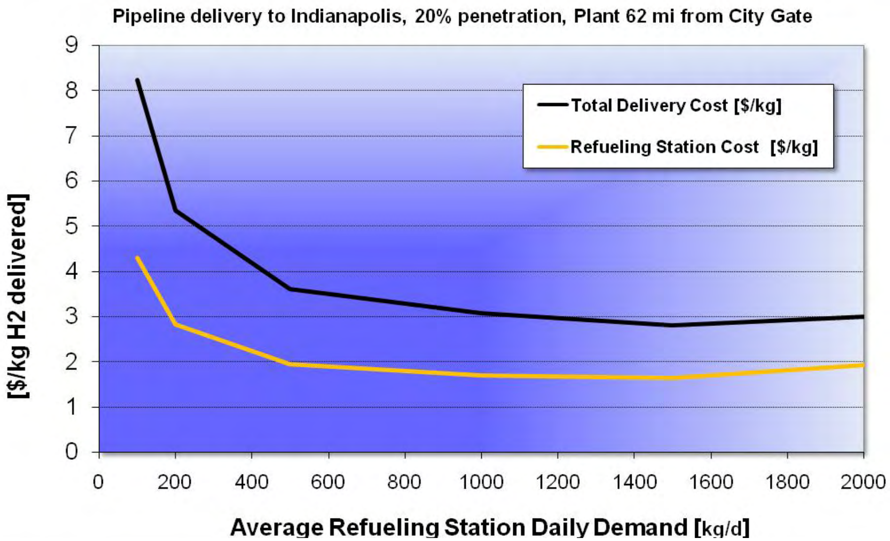
- In V 1.0 cost drops rapidly with increasing demand, up to about 100 tpd
- Scale matters for pipeline and liquid delivery, less so for compressed gas truck
- High pressure gaseous truck may be attractive at low demand, despite uncertain characterization
- V 2.0 reflects same pattern, although most cost estimates are higher
- Most of cost increase for LH2 delivery in V 2.0 is due to 200 tpd liquefier size limit

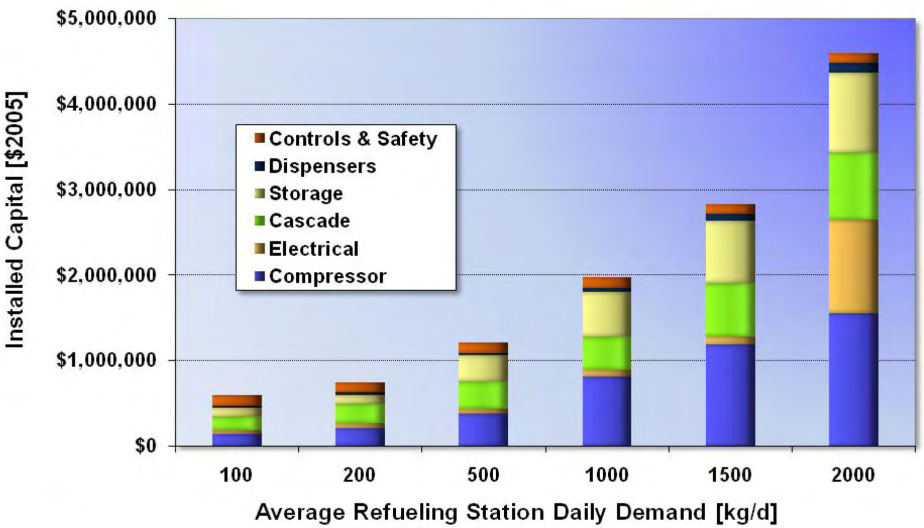
Much of the Increase Is in Capital Cost



- In both H2A Delivery Models, gaseous truck delivery is less capital intensive at low demand
- High pressure gas truck (not modeled in V 2.0) may be even less capital intensive
- Unit capital cost of all delivery modes flatten, becoming comparable beyond 100 tpd
- Energy & other O&M gain importance at higher demand
- Each mode has a major capital cost challenge, particularly at low demand

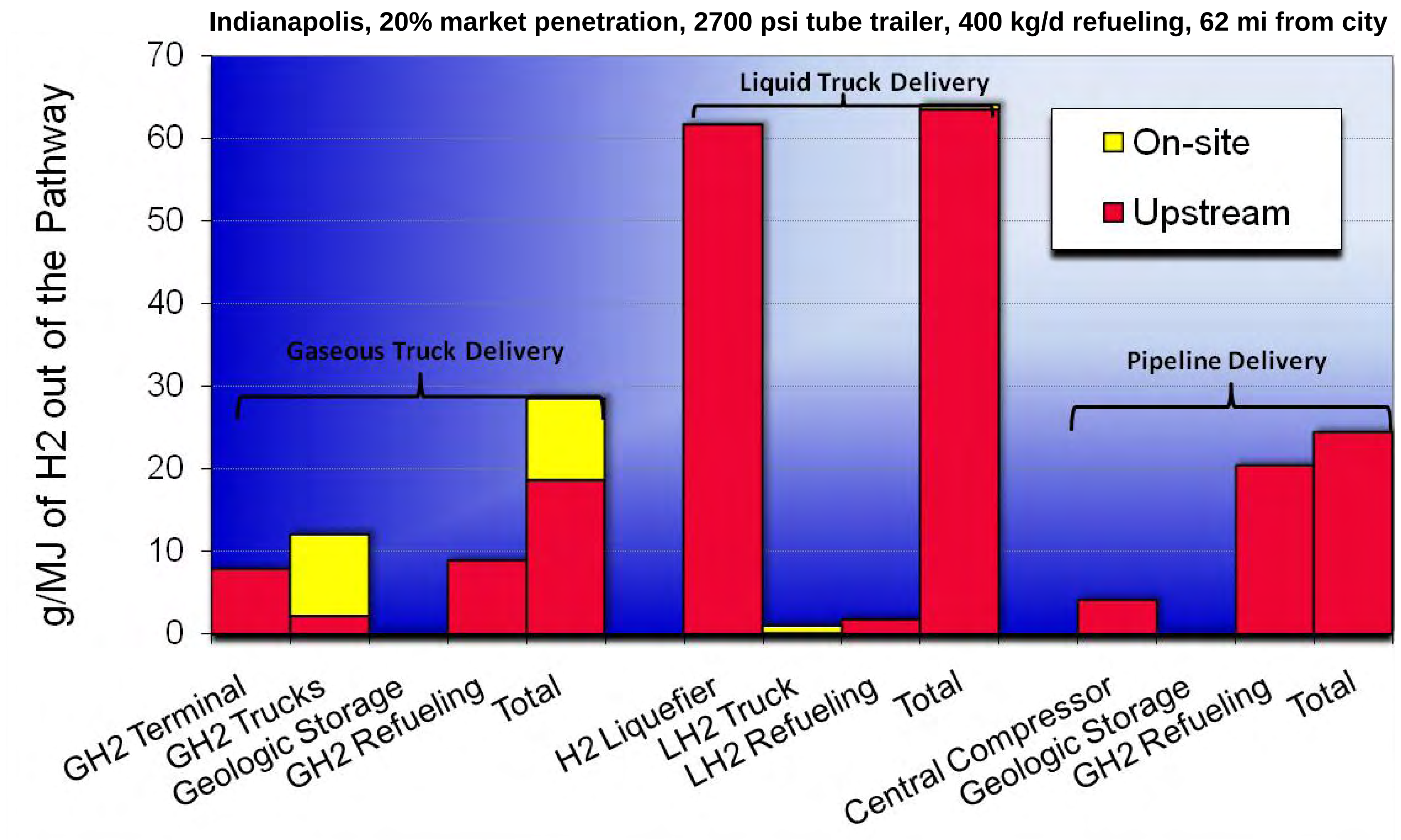
Refueling Stations Account for More Than Half the Cost of Delivering Hydrogen With Current Technologies





- Both total delivery and refueling station costs decline with scale, to ~ 1500 kg/d
  - Delivery cost drops from $8.23 to $2.80/kg
  - Refueling stations from $4.30 to $1.64/kg
- **Even at stations dispensing 1500 kg/d, delivery cost exceeds EERE's 2012 and 2017 targets ($1.70/kg and $1.00/kg)**
- Installed capital represents 75% station cost
- Cascade and compression account for bulk of cost of smaller stations; above 500 kg/d storage exceeds cascade costs
- In larger stations, electrical upgrades become significant
- Extreme peaking of demand in peak hour **increases compressor and cascade system costs**

Due to Liquefaction's Energy Intensity, Liquid Truck Delivery Emits More GHGs Than Other Modes



Future Work

Month/Year	Milestone
August 2008	Revise Users' Guides and post on EERE website.
December 2008	Complete and post Version 2.5 of H2A Delivery Models on EERE website. Expansions focus on refueling station and terminal footprints, component cost and operating procedures (per Delivery Tech Team recommendations), and model enhancements to permit delivery to multiple urban areas.
September 2009	Complete and post Version 3.0 of H2A Delivery Models. Enhancements permit modeling of alternative carriers and other advanced conditioning options (cryo-compressed storage vessels and delivery trucks, 10,000 psi compression, cascade systems and dispensing).

Project Summary

- **Relevance:** Identify aspects of hydrogen delivery that are especially costly (in $, energy and GHG emissions) and estimate impact of alternative conditioning, storage and distribution options on those costs.
- **Approach:** Develop models of hydrogen delivery components and systems to quantify costs and permit analyses of alternative technologies and operating strategies.
- **Collaborations**: Active partnership among ANL, NREL, PNNL, Nexant and TIAX plus regular interaction with OFCHIT's Fuel Pathways and Delivery Tech Teams.
- **Technical accomplishments and progress:**
  - Data collection and analysis of compressors, liquefiers, storage terminals, local distribution pipelines, cascade charging systems, storage vessels, fuel stations
  - Delivery system optimization for storage, compression, and cascade charging to accommodate seasonal demand variations, production plant maintenance schedules, and daily and hourly refueling demand
  - Version 2.0 of H2A Delivery Models and associated documentation
  - Analysis of alternative hydrogen carriers
- **Future Research**: Expand models to include new technologies (cryo-compressed gas, alternative carriers, 10,000 psi) and incorporate Tech Team recommendations.

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