2009 DOE Hydrogen Program Review

Hydrogen Delivery Infrastructure Analysis

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Argonne NATIONAL LABORATORY

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Overview

Timeline

- Start: FY 2007
- End: Continuous

Budget

- 100% DOE funding
- FY08: $460 k
- FY09: $400 k

Barriers

- Lack of H2/carrier infrastructure options analysis
- Cost of delivery components
- Cost of hydrogen storage system
- Dispensing technology requirements
- Storage system lifecycle assessment

Partners

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

Project Objectives

- Model hydrogen infrastructure requirements
  - Pathway and component characterization
  - Dispensing and off-board storage requirements
  - Lifecycle analysis (WTT energy and greenhouse gas emissions)
- Explore options to reduce the cost of hydrogen infrastructure and delivery
  - System storage requirements and tradeoffs
  - Hydrogen carriers and other advanced delivery options
  - Alternative dispensing strategies
- Enhance models to assist in program planning/review
  - Additional/revised pathways, markets, technologies
  - User options
  - Industry input and review

Approach

- 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
  - Develop **user-friendly interface** to quickly and easily define scenarios
  - Provide structure to automatically link and size components into **optimized pathways** to satisfy supply and demand requirements of scenario and compute **system delivery** cost
- **Collaborate** to analyze storage, station, dispensing and conditioning options and incorporate findings into Hydrogen Delivery Scenario Analysis Model (HDSAM)
  - Analyze storage, compression, liquid handling, fuel station options and costs
  - Create H2A-like tool to identify and consistently evaluate viable carrier options
- Provide **thorough QA**
  - Internally via partners
  - Externally, via briefings to Tech Teams, early releases to DOE researchers, industry interaction

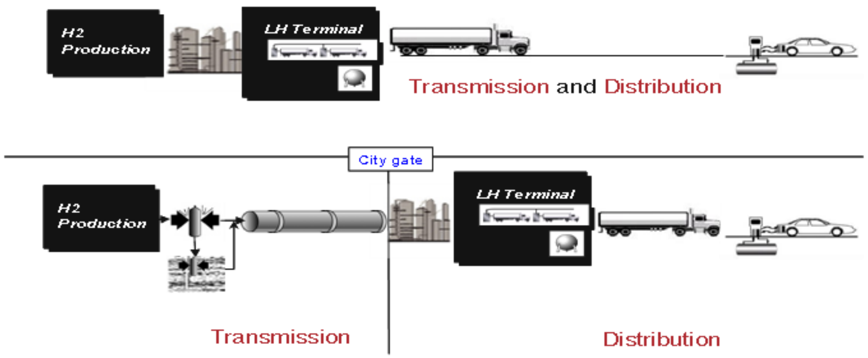
Relevance

- HDSAM provides platform to compare alternative component, subsystem and system infrastructure options:
  - Capital investment
  - Levelized cost
  - Energy
  - Greenhouse gas emissions
- Delivery scenarios permit analysis of options and tradeoffs including:
  - Scenario parameters
    - Market type and size
    - Fuel station capacity and configuration
  - Delivery components/major equipment
    - Unit cost
    - Capacity/scale
    - Reliability/utilization, etc.
  - Subsystem tradeoffs and optimization
    - Site storage vs. peak capacity
    - Fuel station configuration and dispensing requirements
  - System optimization
    - Bulk storage
    - System storage vs. peak capacity

FY09 Accomplishments

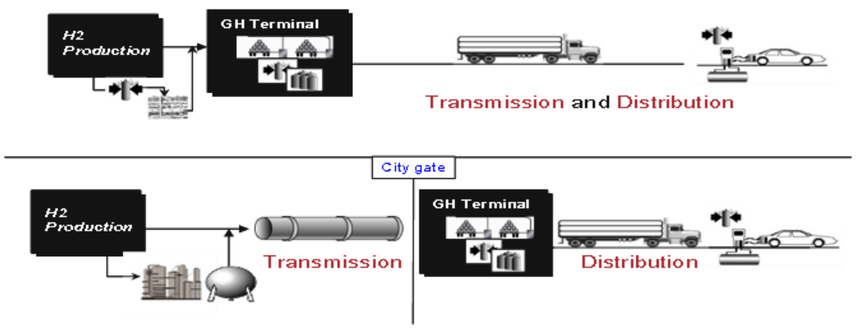
Month/Year	Milestone
Oct 2008	Version 2.0 of Hydrogen Delivery Scenario Analysis Model (HDSAM 2.0) and Users Guide
Nov 2008	**700-bar pathway**
Dec 2008	**Cryo-compressed (CcH2) pathway**
April 2009	**Post-delivery purification analysis**
May 2009	**High pressure tube trailer**
June 2009	Fuel station footprint analysis
Sept 2009	Multiple markets
Oct 2009	HDSAM 2.1 and Users Guide

HDSAM 2.0 Models Transmission, Distribution & Bulk Storage Needed to Meet Scenario-Defined Supply & Demand



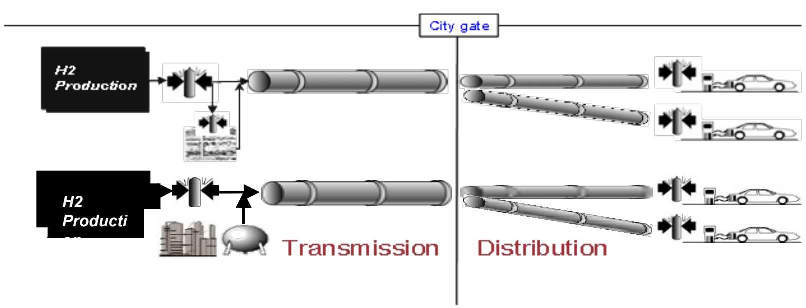
Liquid H2 Distribution Pathways

- Bulk geologic or liquid hydrogen storage
- Pipeline or truck transmission
- Urban, interstate or combined markets
- 50-6000 kg/d GH2 fuel stations
- \+ LH2 storage and cryo-compressed (CcH2) dispensing



Compressed GH2 Distribution Pathways

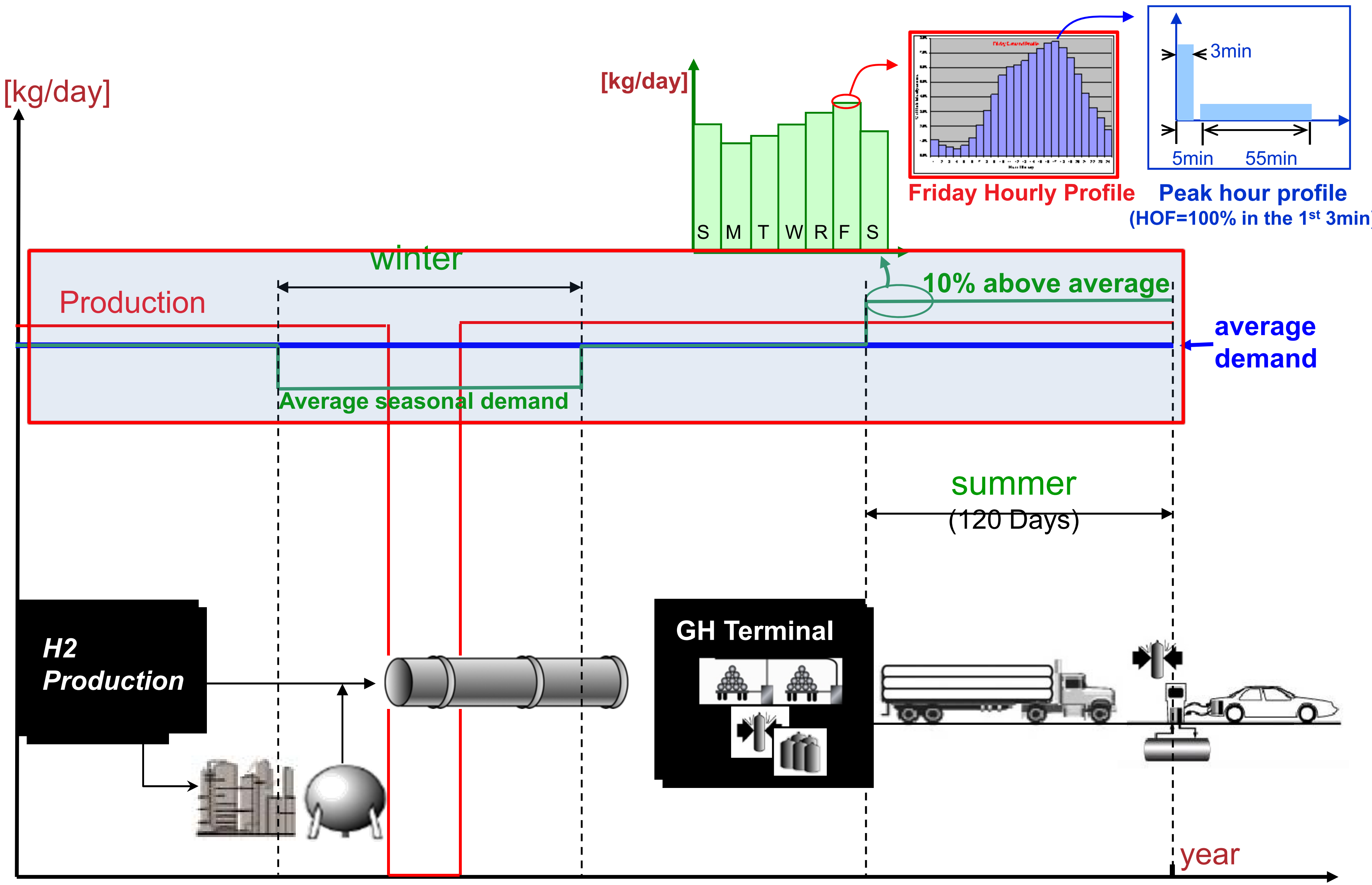
- Bulk geologic or liquid hydrogen storage
- Pipeline or truck transmission
- Urban, interstate or combined markets
- 50-6000 kg/d GH2 fuel stations
- \+ 700-bar dispensing
- \+ GH2 purification
- \+ High pressure tube trailer delivery



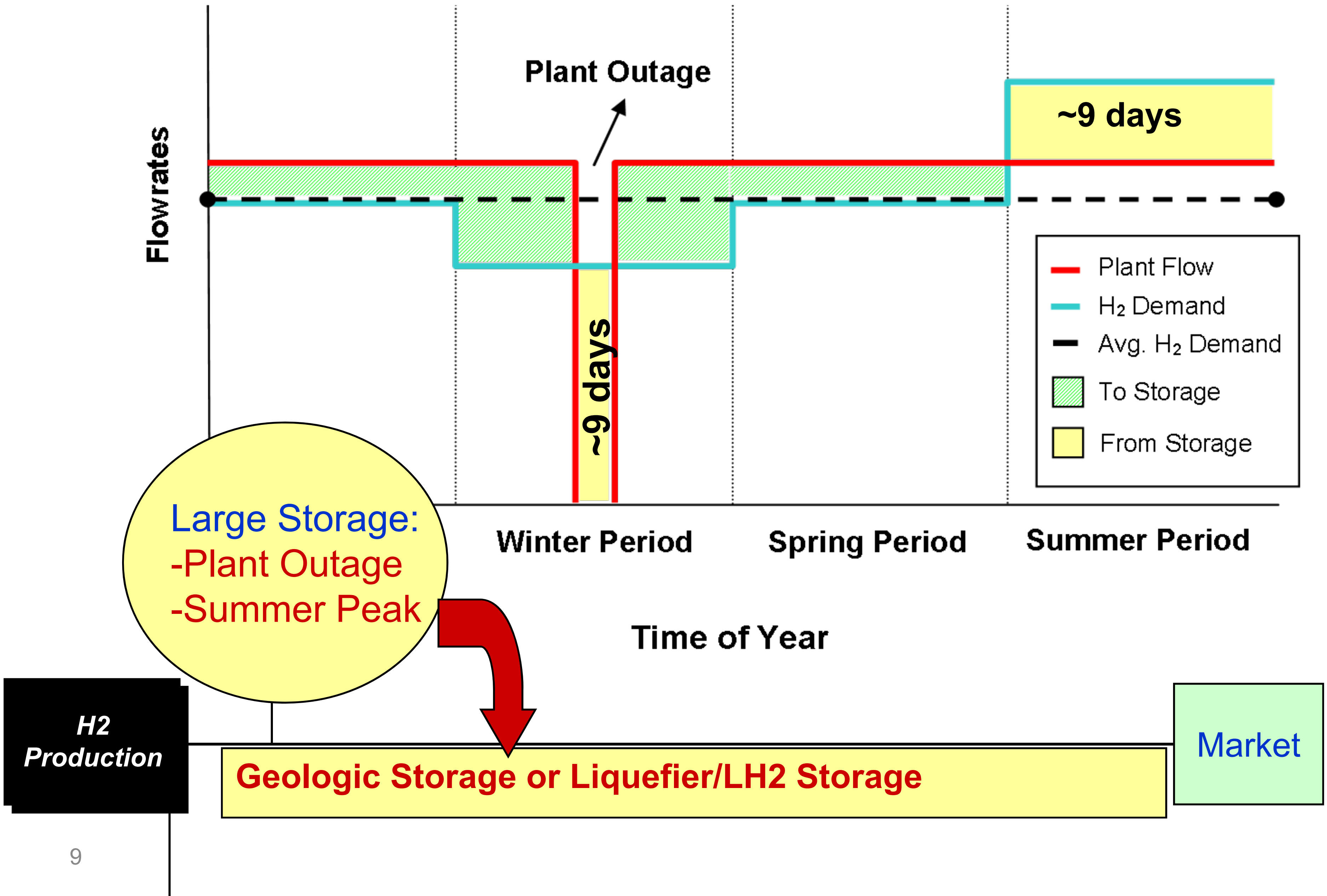
Pipeline Distribution Pathways

- Bulk geologic or liquid hydrogen storage
- Urban, interstate or combined markets
- 50-6000 kg/d GH2 fuel stations
- \+ 700-bar dispensing
- \+ GH2 purification

Supply & Demand Profiles Define Infrastructure Capacity



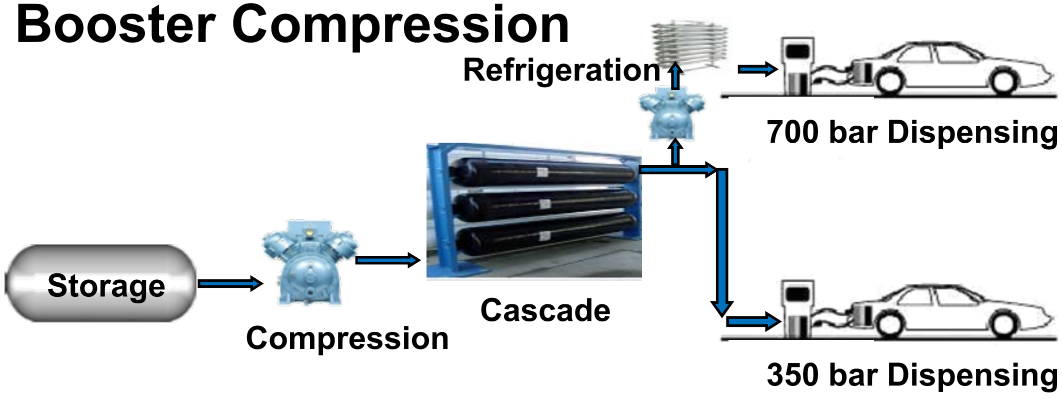
Bulk Storage Depends on Variability of Supply & Demand



700-BAR,
CRYO-COMPRESSED, AND
HIGH-PRESSURE TUBE TRAILER PATHWAYS

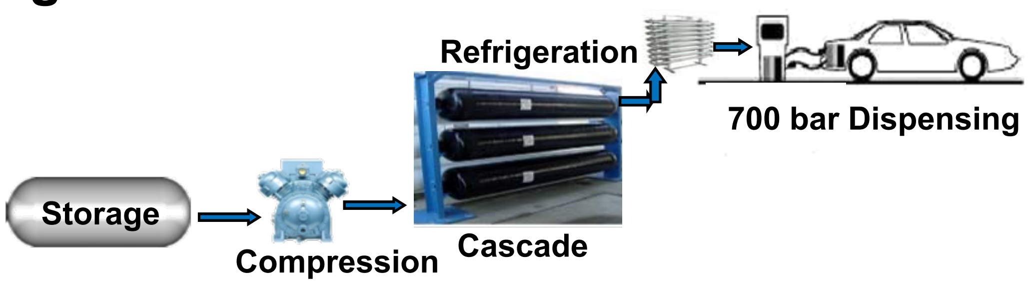
Two 700-bar GH_2 Fuel Station Configurations Are Modeled

Booster Compression



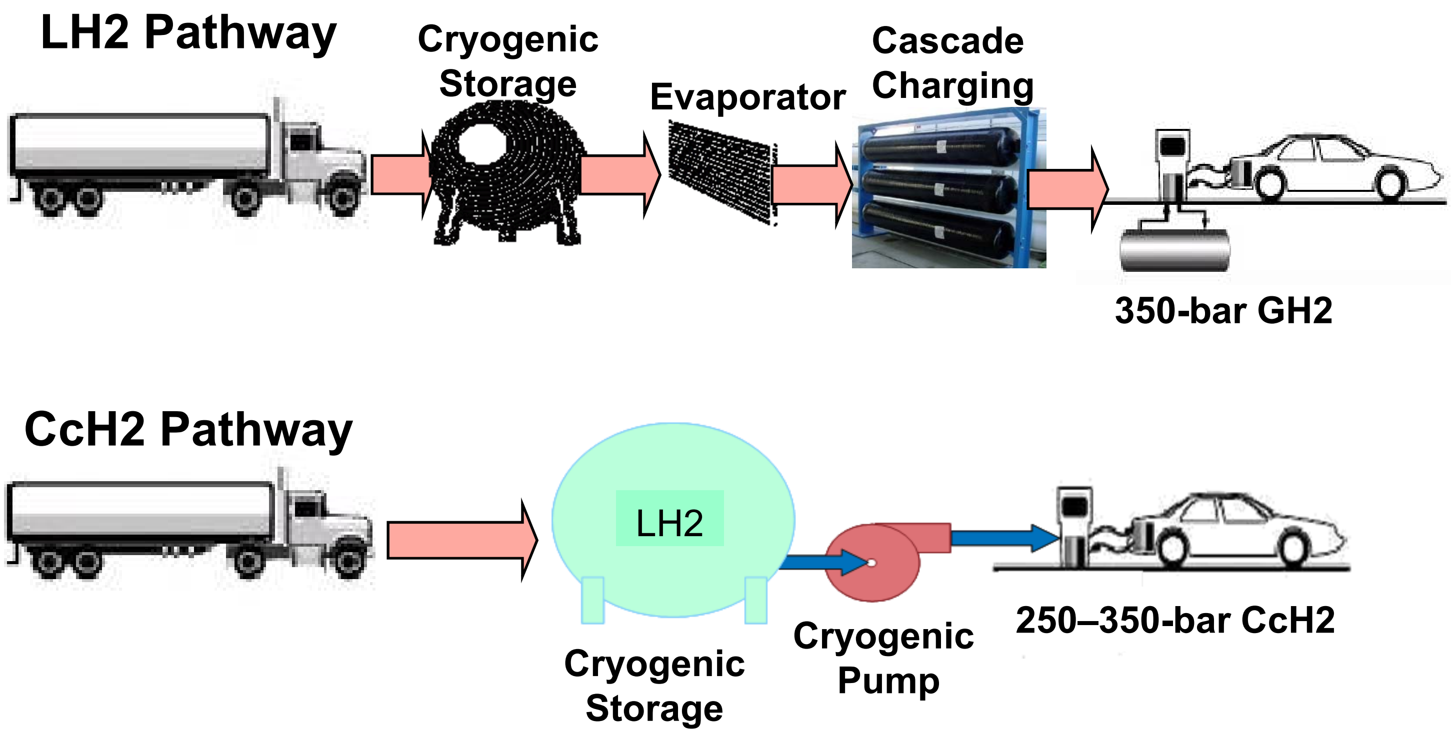
- Booster compressors: $167,000 (uninstalled); 1 per hose.
- Refrigeration (both booster and cascade): 15 T for 1000 kg/d station; COP 1.3 for -40 C cooling; $6000/T refrigeration (T=12,000 Btu/hr, uninstalled).

High Pressure Cascade



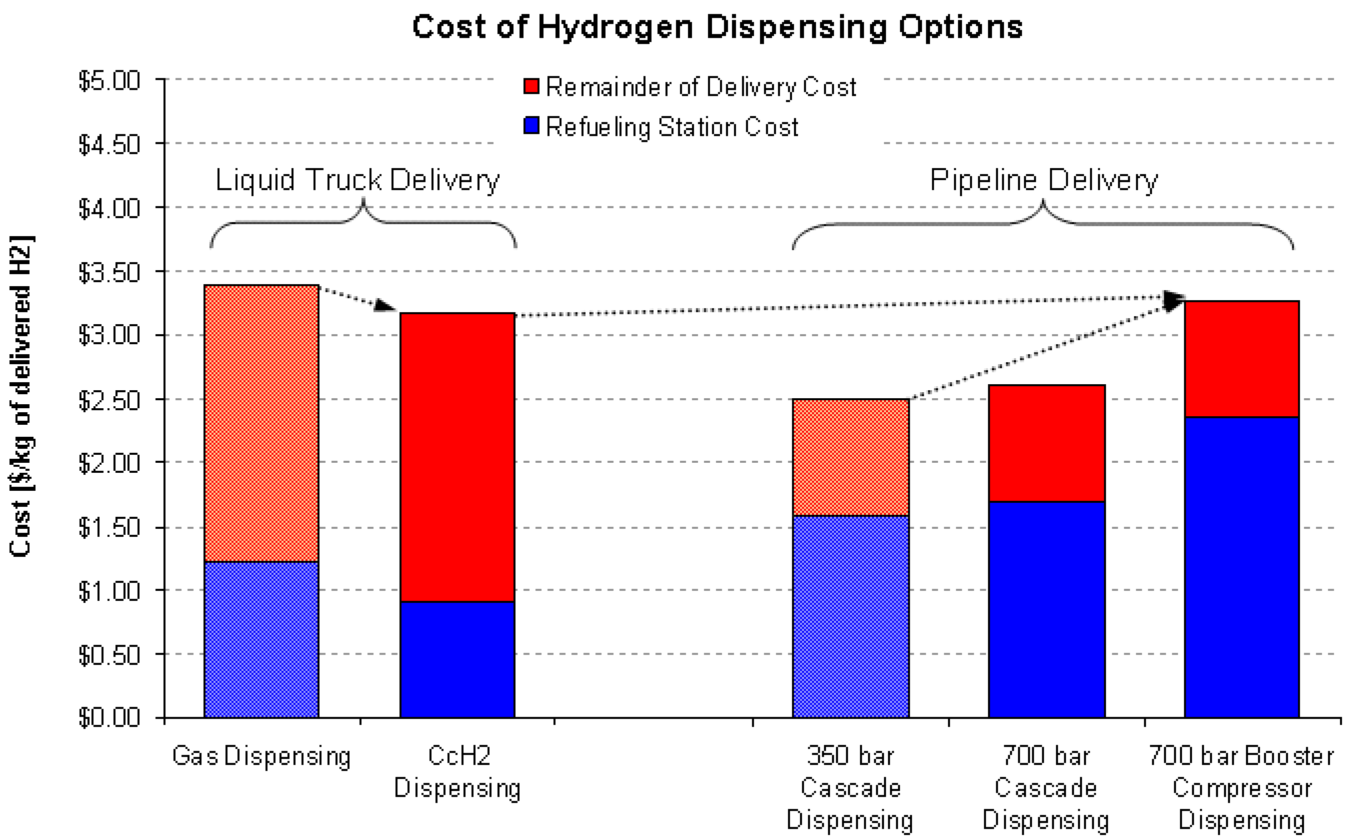
- High pressure cascade: $1450/kg of storage (uninstalled).

One Cryo-Compressed (CcH2) Dispensing Option Is Modeled, as an Alternative to LH2 Truck Distribution



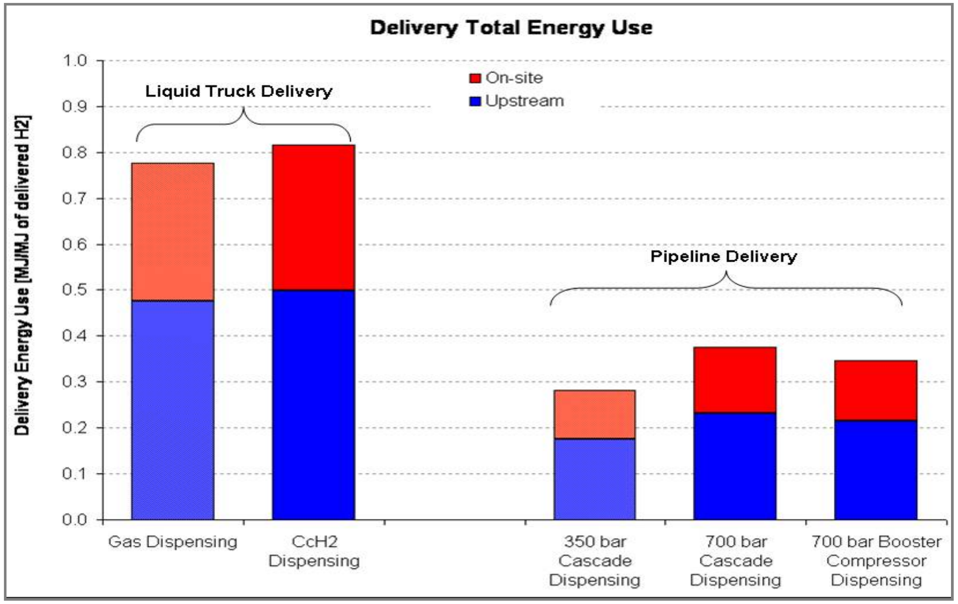
- Cryo-pumps: $260,000 (installed, 1000 units); 100 kg/hr capacity, 350 bar.
- Boiloff: 6 % of average daily demand.
- **Since CcH2 dispensing eliminates cascade and evaporator, cost should drop**.

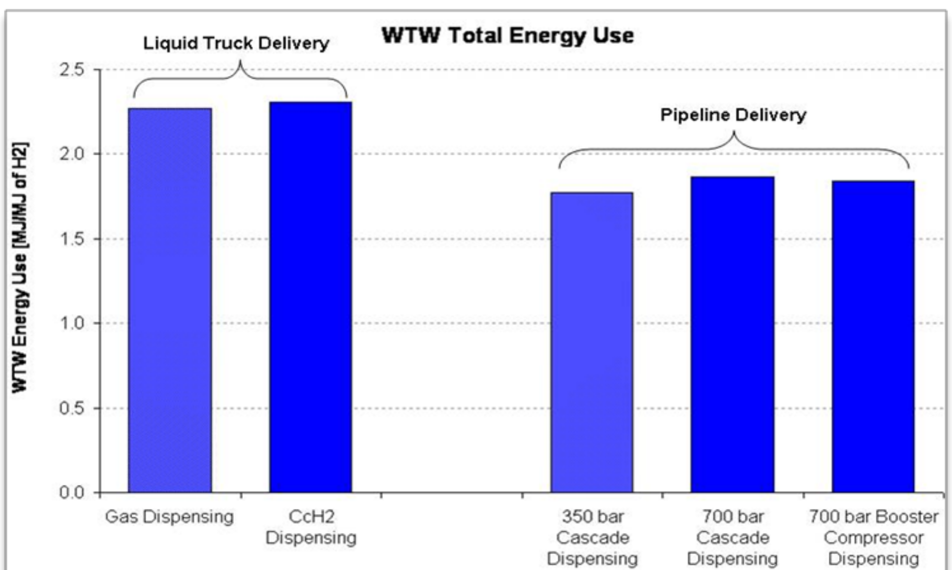
Station Costs Rise with 700-Bar Dispensing of Pipeline-Delivered GH2 but Drop with CcH2 Dispensing



- CcH2 dispensing is less expensive than GH2 dispensing of vaporized LH2.
- **700-bar GH2 using high pressure cascade is only slightly more expensive than 350-bar GH2**. Booster-compressed 700-bar dispensing is more expensive.
- Although **LH2 truck delivery cost with CcH2 dispensing is comparable to 700-bar** dispensing using boost compression, more of the cost occurs at the station for 700-bar.

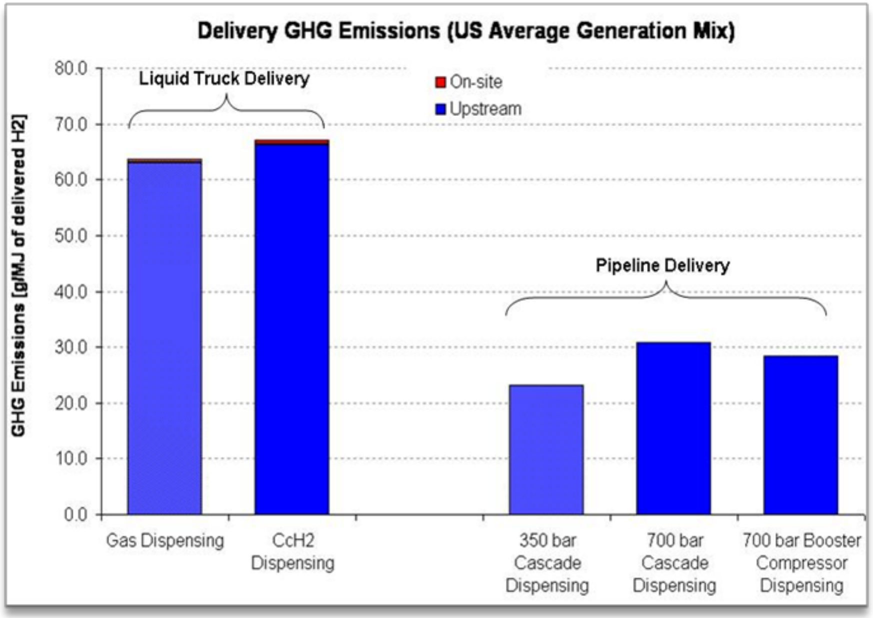
Delivery: Energy Use

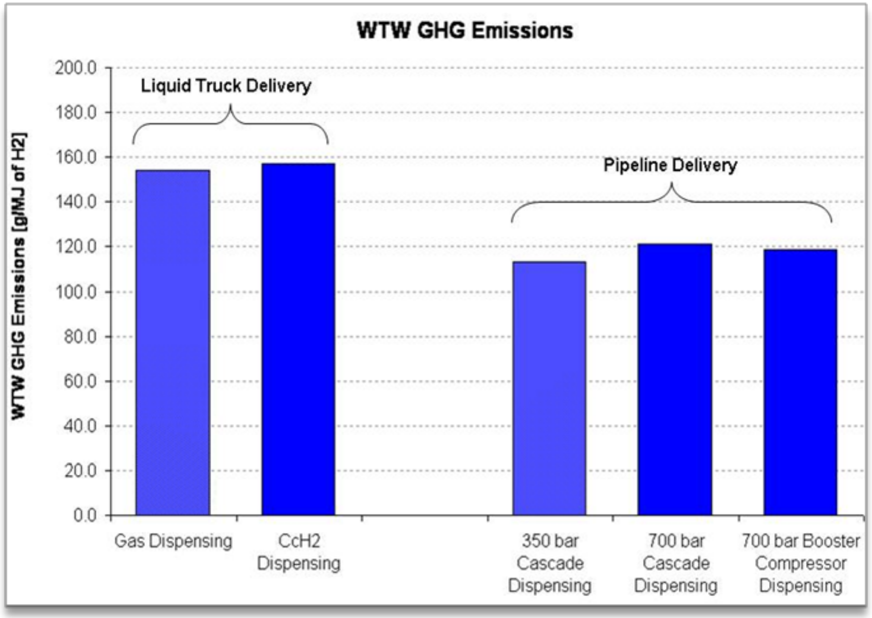




- LH2 truck delivery (top graph) is most energy intensive pathway, consuming more energy on-site as well as upstream.
- Including production (bottom graph), relatively little electricity is used, thus little energy is consumed upstream.
- By itself, **liquid delivery** (including liquefaction) **uses more than twice as much energy as pipeline delivery**.
- But **when production is included** (bottom graph), differences narrow (liquid delivery uses only 25–30% more energy).

Delivery Greenhouse Gas Emissions

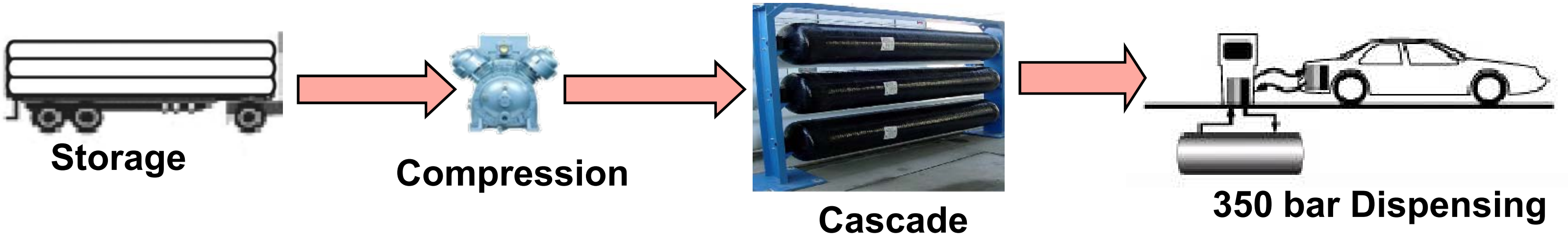




- Virtually all GHG emissions occur upstream of the fuel station.
- **Excluding production** (left graph), **LH2 delivery emits twice as many GHGs as pipeline delivery.**
- **Including production** (right graph), the **difference drops to ~30%.**

One High-Pressure GH2 Tube Trailer Configuration Is Modeled

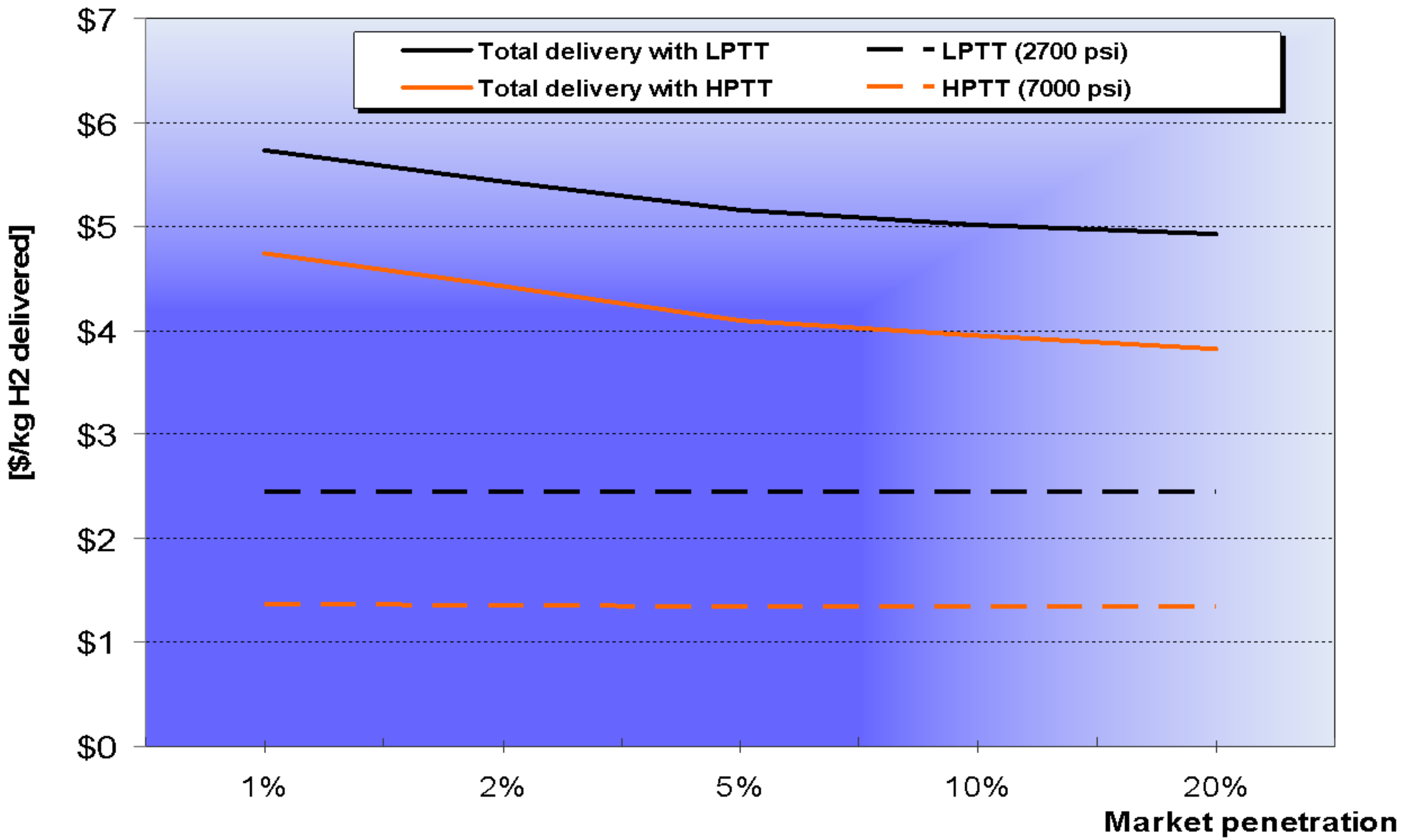
High-Pressure Tube Trailer Pathway



- Maximum tube pressure:7000 psi
- Capacity: 700 kg
- Cost: $350,000
- Fill time at terminal: 10 hrs

Dynetek Announces US DOT Approval of 6500 PSI Cylinder for Bulk Transport Systems, May 29, 2008, http://www.dynetek.com/library/files/BT450_USDOT_Approval.pdf.

Tube Trailer Delivery Drops ~$1.00/kg with High Pressure Trailers

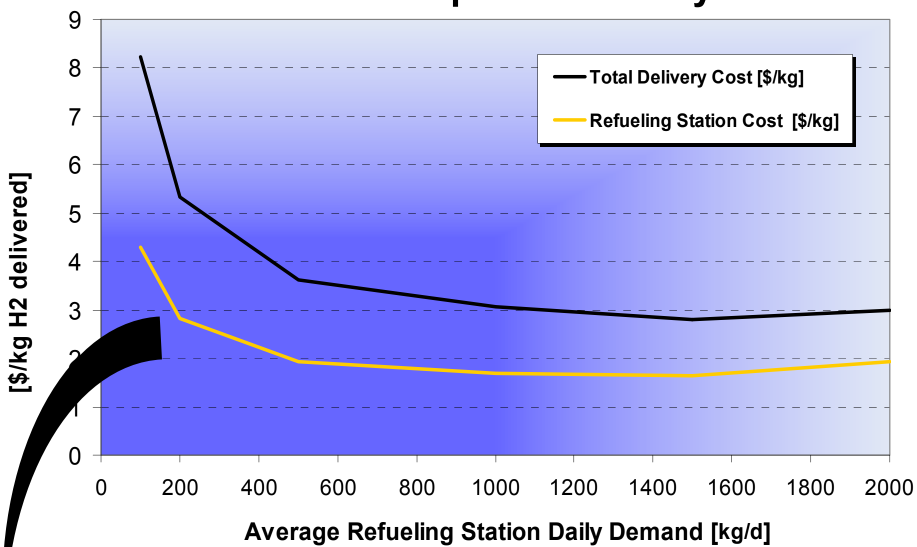


Indianapolis, 350 bar dispensing, 300 kg/day Station, 62 miles to City

FUEL STATION COST

Refueling Stations Account for >Half Cost of GH2 Delivery

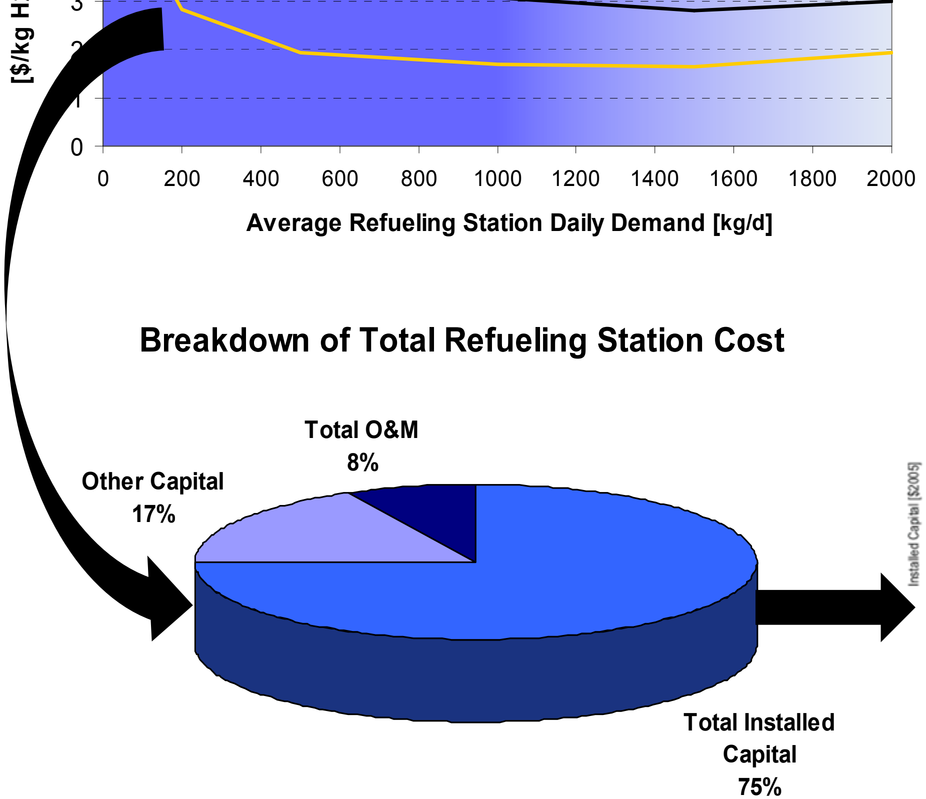
Cost of Pipeline Delivery



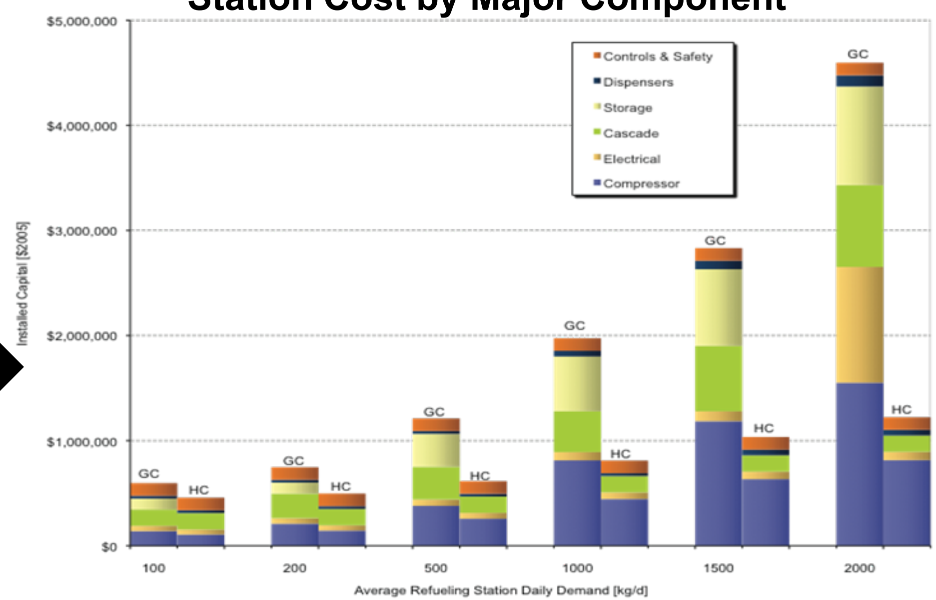
- Delivery and fuel station costs decline with scale, to ~ 1500 kg/d
  - Delivery drops from \$8.23 to \$2.80/kg
  - Refueling stations from \$4.30 to \$1.64/kg
- Even at 1500 kg/d stations, delivery exceeds EERE's 2012 and 2017 targets (\$1.70/kg and \$1.00/kg)
- Depending on average daily demand, fuel stations account for 52-64% of pipeline delivery cost (<35% for LH2 delivery at stations > 500 kg/d)
- Installed capital represents 75% station cost
- At larger stations, electrical upgrades become significant
- Compression & storage ~2/3 installed capital (1000–1500 kg/d stations)

… Reducing pipeline delivery cost requires lower compression and storage costs

Breakdown of Total Refueling Station Cost

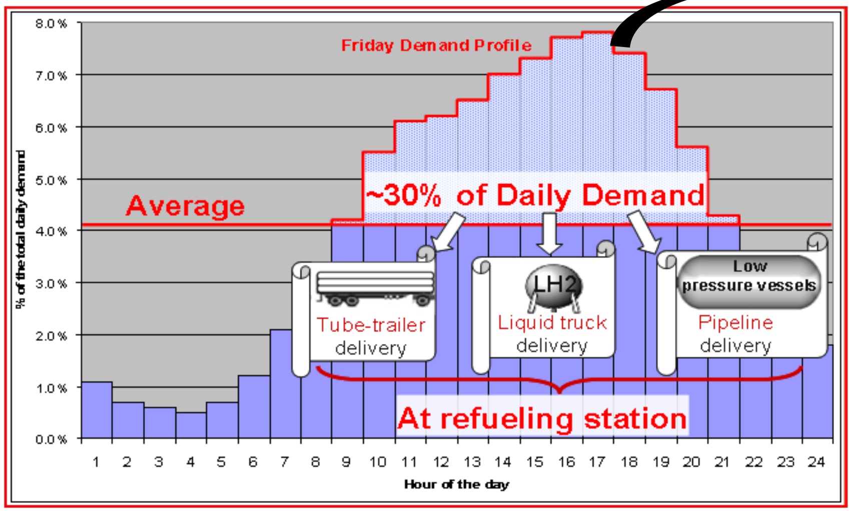


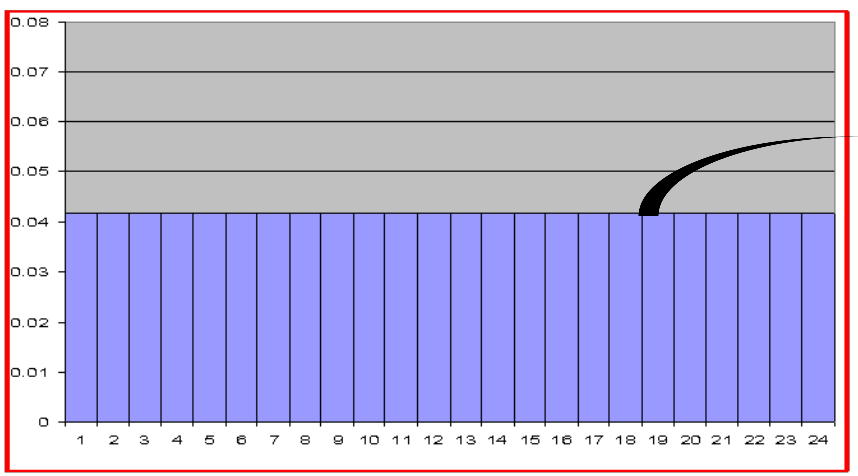
Station Cost by Major Component



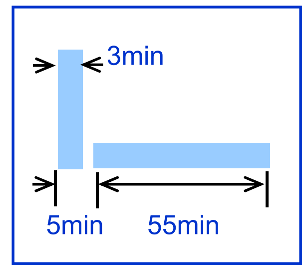
Default Demand Profile Requires Storage for Peak Daily Demand, Compressors Sized to 2x Hourly Flow

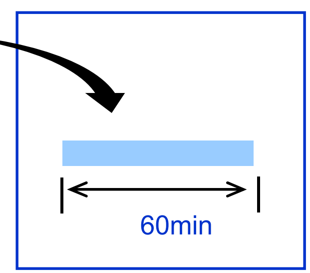
Hourly Demand for Peak Day in Peak Season





Demand in Peak Hour
(HOF=100% in the 1st 3min)

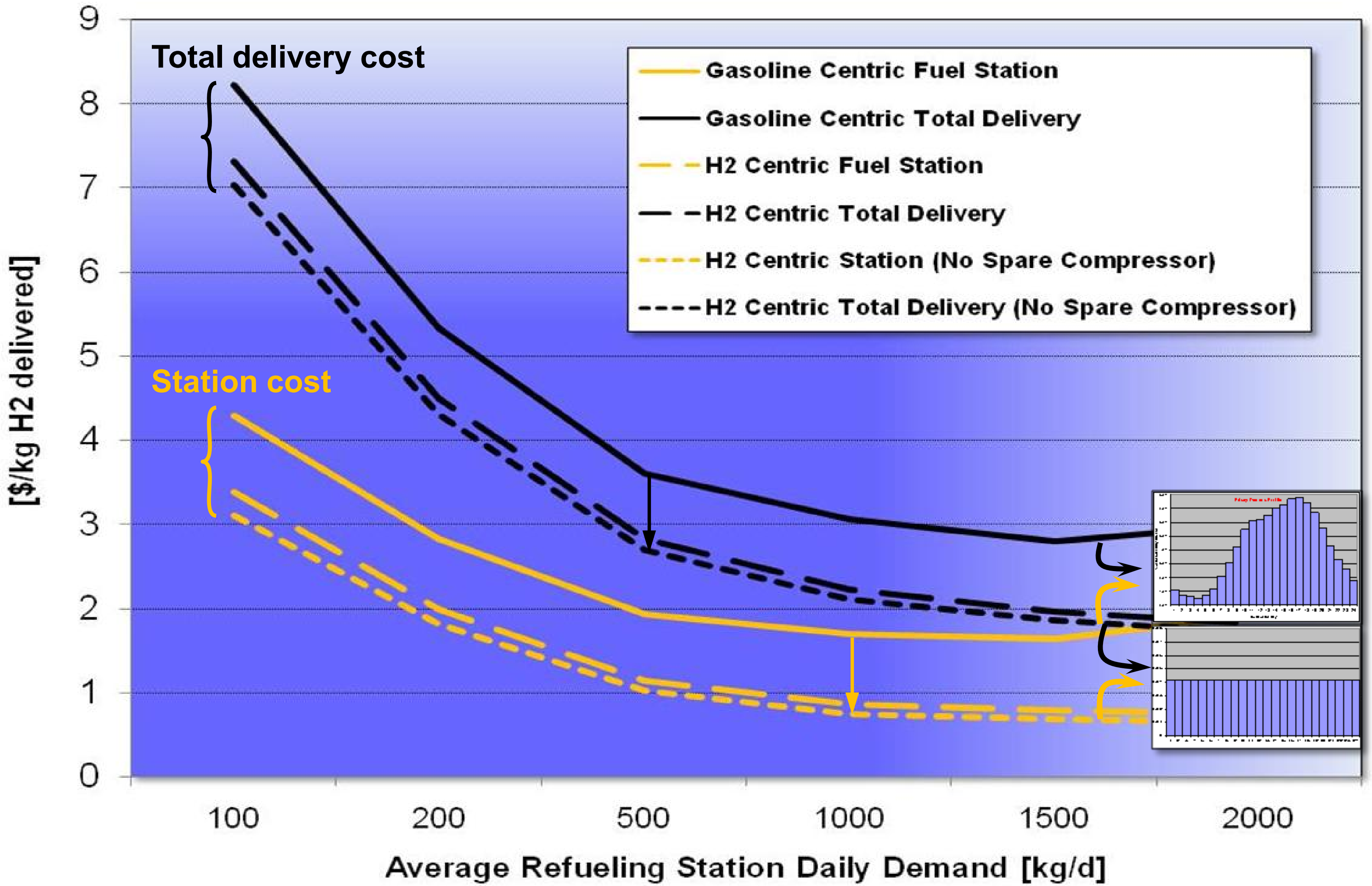




- Extreme peaking in peak hour increases compressor, dispenser, and cascade system costs.
- Compressors still must be sized to meet DOE fast fill target.

Station storage needs depend on **peak day** demand. Compression cost depends on Δp, flow rate, reliability.

Delivery Cost Drops by ~$1.00/kg for a Flat or "Hydrogen Centric" Demand Profile

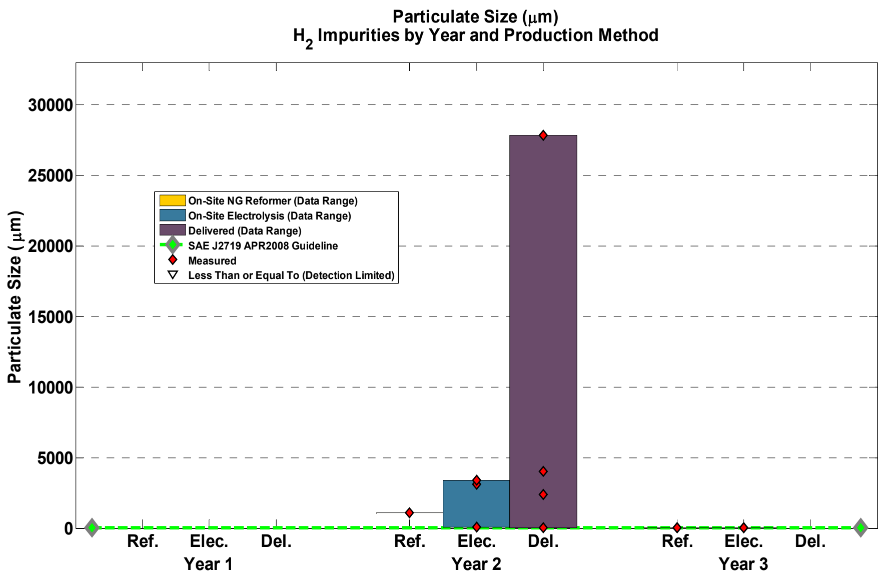


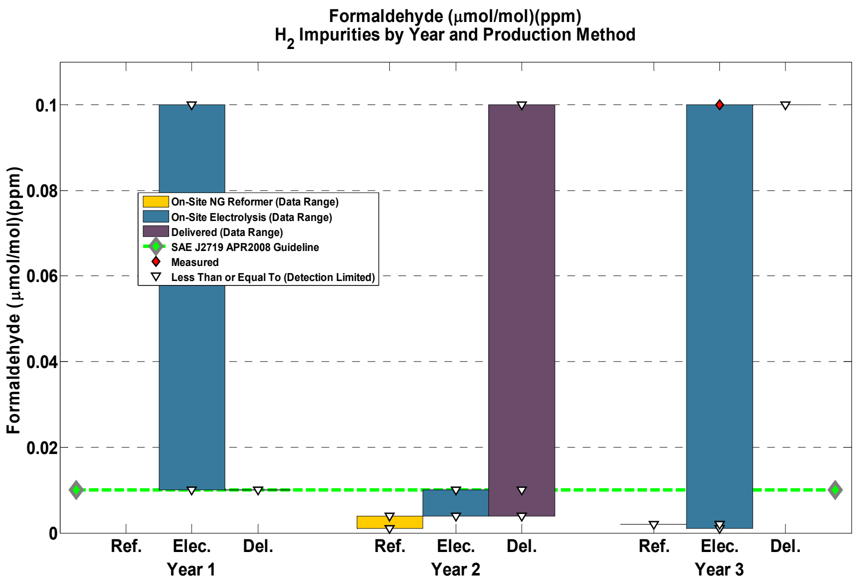
By avoiding electrical upgrade, savings are greater at larger fuel stations.

POST-DELIVERY PURIFICATION ANALYSIS

Scope of Post-Delivery Purification Analysis

- Verify need for post-delivery cleanup
  - Delivered GH2 vs. SAE J2719 specification
  - Data gaps/issues
    - **Test methods : ASTM D03 developing standards**
    - **Measured impurities at Learning Demos: some below detection limit (e.g., formaldehyde)**





- Estimate cost to remove contaminants
- Revise HDSAM GH2 fuel station configurations, add cleanup cost equations, revise GUI, review and QA

Current Measures of US Post-Delivery Fuel Quality Are Inconclusive

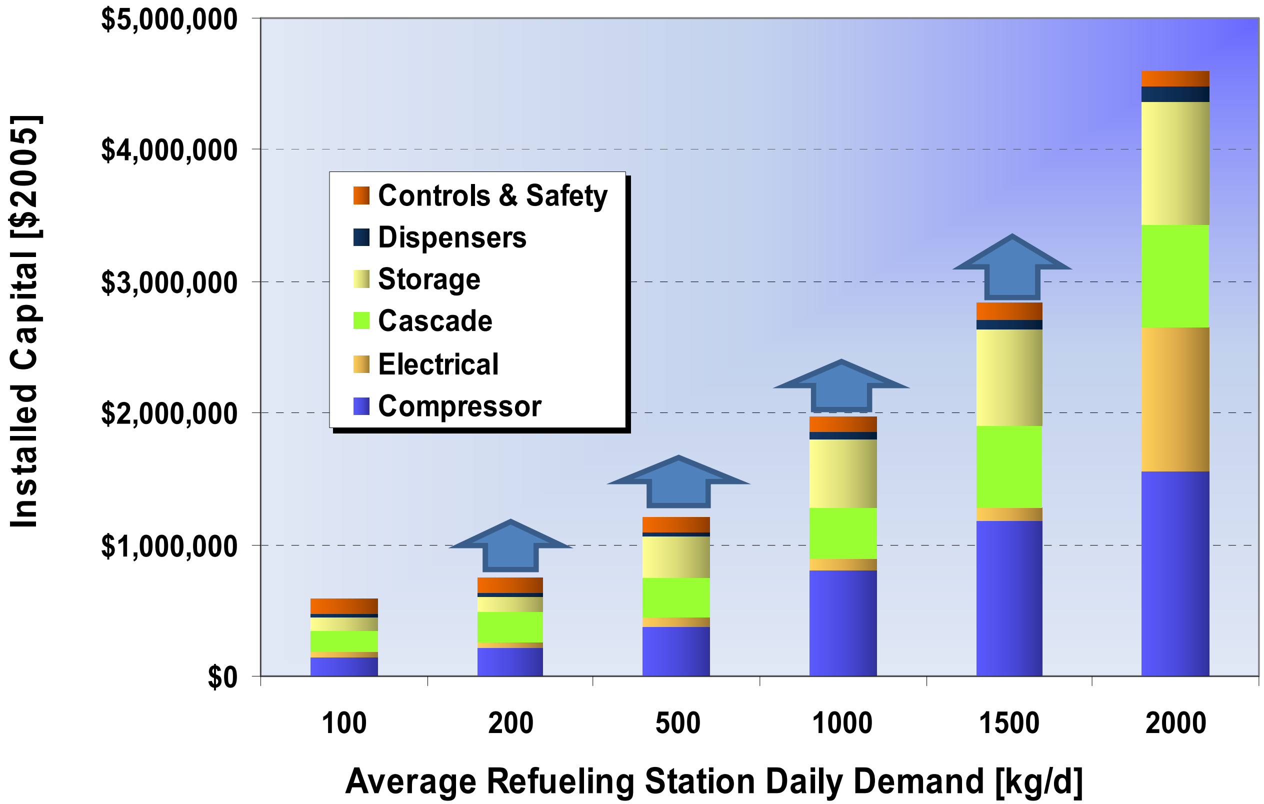
SAE J2719 Hydrogen Fuel Cell Quality Specification

Name	Units	Formula	Amount
Hydrogen fuel index	vol%	H_2	>99.99%
Non-hydrogen constituents	ppm or		
Total Non-Particulates	µmol/mol [a]		100
Water [b]	µmol/mol	H_2O	5
Total hydrocarbons [c] (C_1 basis)	µmol/mol		2
Oxygen	µmol/mol	O_2	5
Helium, Nitrogen, Argon	µmol/mol	He, N_2, Ar	100
Carbon dioxide [d]	µmol/mol	CO_2	1
Carbon monoxide	µmol/mol	CO	0.2
Total sulfur [e]	µmol/mol		0.004
Formaldehyde	µmol/mol	HCHO	0.01
Formic acid	µmol/mol	HCOOH	0.2
Ammonia	µmol/mol	NH_3	0.1
Total halogenates [f]	µmol/mol		0.05
Max. Particulate Size	µm		< 10
Particulate Concentration	µg/L H_2		1

- Particulates at learning demonstration sites exceed J2719 fuel quality spec (shown at left).
- J2719 spec is below detection limits of tests for total sulfur (0.028), formaldehyde (0.1) and ammonia (1.0) at Learning Demonstration sites.
- **Delivered GH2 at current learning demonstrations may or may not meet J2719 requirements.**
- ASTM D03 committee is developing recommended test procedures for measuring sulfur, ammonia, formaldehyde and other contaminants to J2719 specifications.

Assuming Contaminant Concentrations at the Limit of Current US Sampling Devices, Gas Cleanup Could:

- Add >$500,000 to capital cost of 1500 kg/d station (~20%), nearly as much to smaller stations.
- Increase delivery cost ($/kg) unless unrecovered hydrogen (PSA tail gas) at the station can be used for other thermal needs.
- Increase energy and GHG emissions due to relatively low recovery efficiency (unless tail gas can be used for other thermal needs).



……. But until testing confirms that additional cleanup is needed, it is premature to add further purification to HDSAM

Future Work

Month/Year	Milestone
July 2009	Revise fuel station footprint.
September 2009	Expand market definitions to permit delivery pathways to serve multiple urban markets.
October 2009	Complete and post HDSAM 2.1 and revised Users' Guide on EERE website. Expansions focus on CcH2, 700-bar and high-pressure tube trailer pathways, post-delivery purification, revised station footprints and enhancements to permit delivery to multiple markets.
October 2010	Complete and post HDSAM 2.2. Enhancements include additional CcH2 dispensing pathways (dual CcH2 & GH2 dispensing for liquid distribution, CcH2 with pipeline distribution), revised modeling of generic geologic storage and terminal footprint, LA-specific delivery, and advanced compression.

Project Summary

- **Relevance:** Provide platform to identify most costly aspects of hydrogen delivery (in $, energy and GHG emissions), estimate impact of alternative conditioning, distribution and storage options on costs; incorporate advanced options as data become available; assist OFCHIT 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, NREL and PNNL, plus regular interaction with OFCHIT's Fuel Pathways and Delivery Tech Teams, DOE researchers, and gas industry analysts.
- **Technical accomplishments and progress:**
  - Version 2.0 of HDSAM and associated documentation completed and posted
  - Addition of cryo-compressed (CcH2) pathway
  - Addition of 700-bar and high-pressure tube trailer gaseous hydrogen (GH2) pathways
  - Data collection and analysis of post-delivery purification, fuel station footprint, effect of demand profile on station cost
- **Future Research**: Expand models to include new options (additional CcH2 pathways, advanced compression and storage technologies) and markets, revise/update data (station and terminal footprints, cleanup units, geologic storage) and respond to Tech Team recommendations. Analyze implications of results.

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