2019 DOE Hydrogen and Fuel Cells Program
Annual Merit Review

Argonne NATIONAL LABORATORY

Analysis of Cost Impacts of Integrating Advanced On-Board Storage Systems with Hydrogen Delivery

Amgad Elgowainy (PI), Ed Frank, Krishna Reddi, Yusra Khalid, and Jui-Kun Peng
Argonne National Laboratory

Daryl Brown, Energy Technology Analysis

April 30, 2019

SA170

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

- Start: October 2017
- End: Determined by DOE
- % complete (FY19): 70%

Barriers to Address

- Inconsistent data, assumptions and guidelines
- Insufficient suite of models and tools
- Stove-piped/Siloed analytical capability for evaluating sustainability

Budget

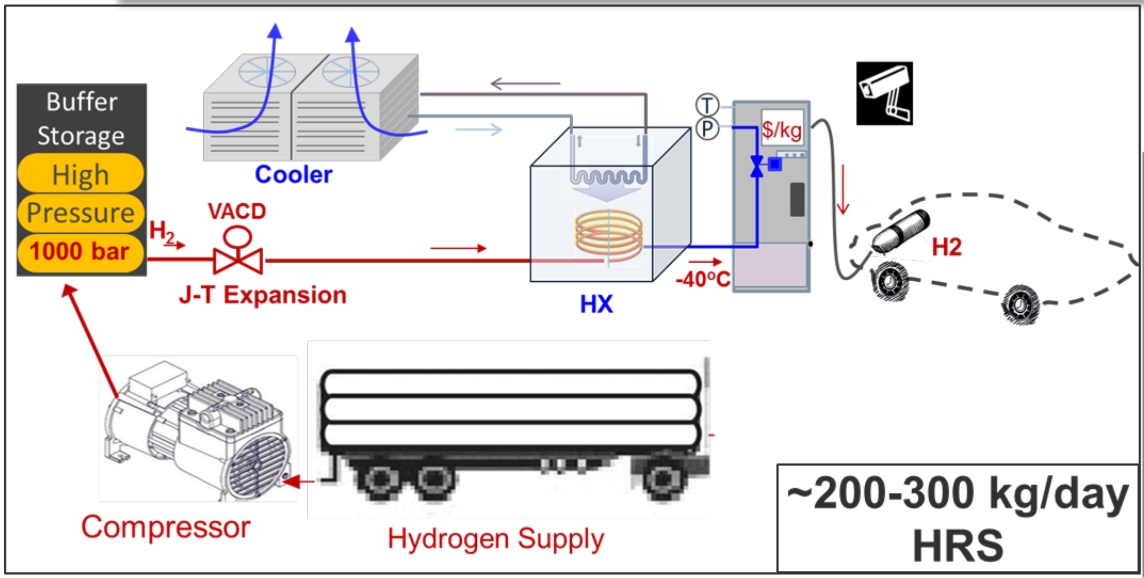
- Funding for FY19: $70K

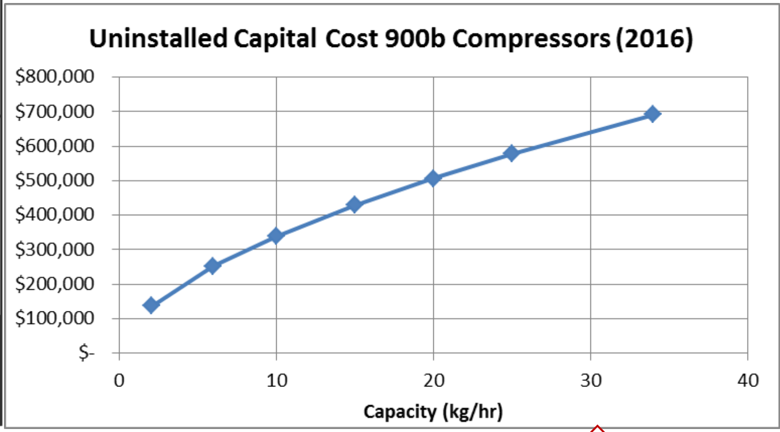
Partners/Collaborators

- U.S.DRIVE: Hydrogen Interface Taskforce (H2IT)
- Energy Technology Analysis (ETA)

Relevance/Impact

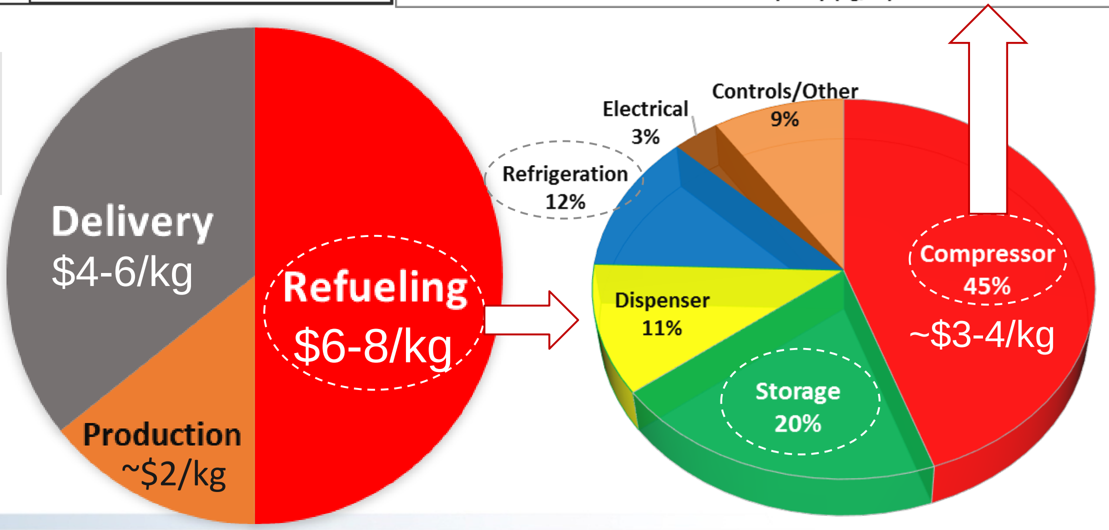
Objective: Evaluate impacts of FCEV on-board storage technologies on levelized cost of hydrogen refueling





Today, hydrogen cost at the dispenser in CA is <u>$13-$16/kg</u>

Bulk of H_2 cost is in delivery and refueling



Pathways for consideration - Relevance

- ✓ 700 bar storage/refueling (baseline)
- ✓ Material Storage:
  - ➢ Metal Hydride (MH) storage/refueling
  - ➢ Sorbent storage/refueling
  - ➢ Cryo-sorbents/refueling
- ✓ Cryo-compressed hydrogen (CcH_2) storage/refueling

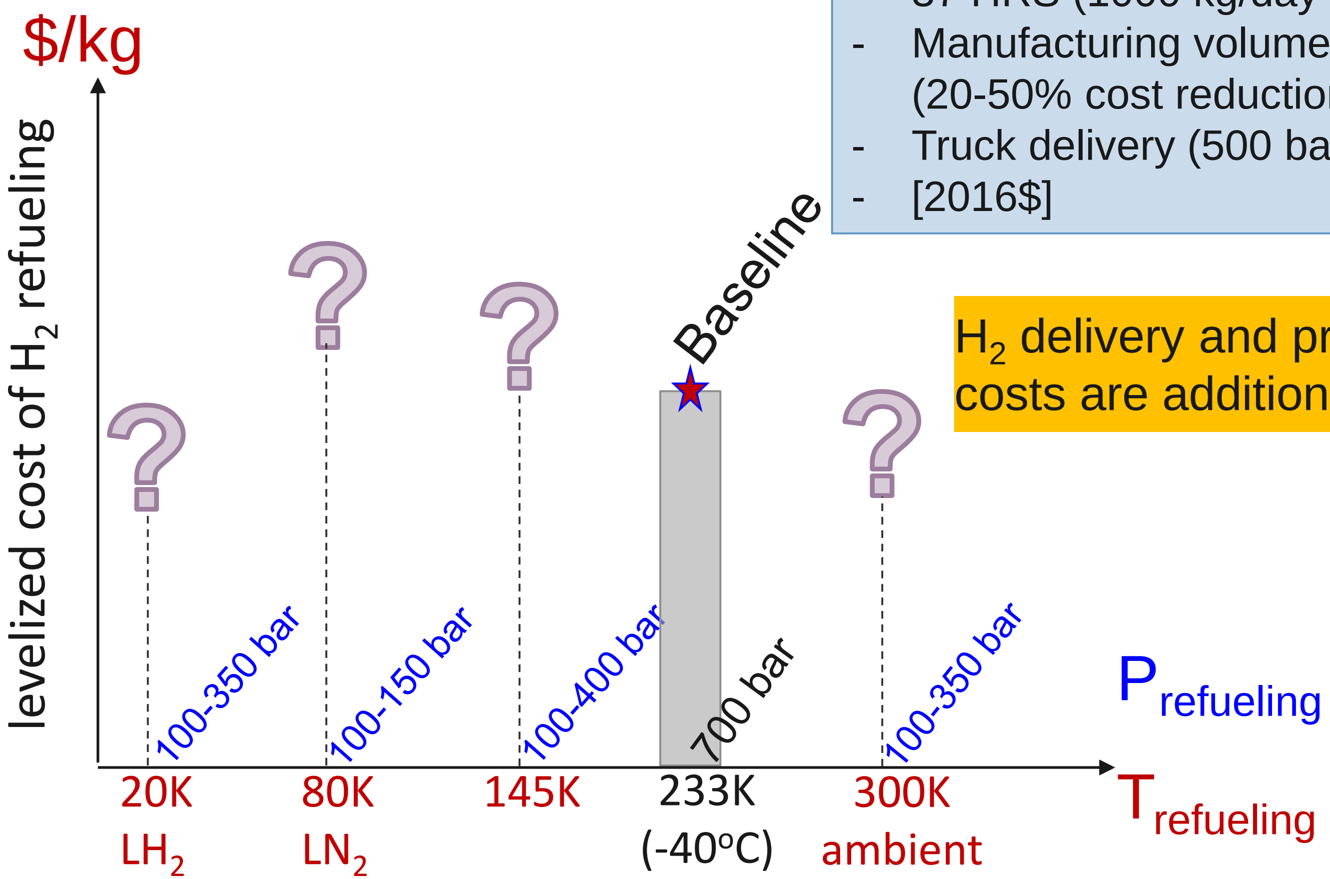
Storage System	System Model Source	Operating Temperature	Operating Pressure
700 bar Compressed H_2	Baseline	Ambient (-40 to 85°C)	5 bar to 875 bar
350 bar Cryo-compressed (CcH_2)	ANL	35 to 93 K	5 to 350 bar
100 bar Cryo-Adsorbent cryo-cooled	ANL	145 to 215 K	5 to 100 bar
Metal hydrides (MH) and Sorbents	ANL	Near ambient to 120^{o}C	5 to 100 bar

Deliverable of Analysis - Objective

- **Evaluate impact of P-T tradeoffs on levelized cost of hydrogen refueling [$/kg]**

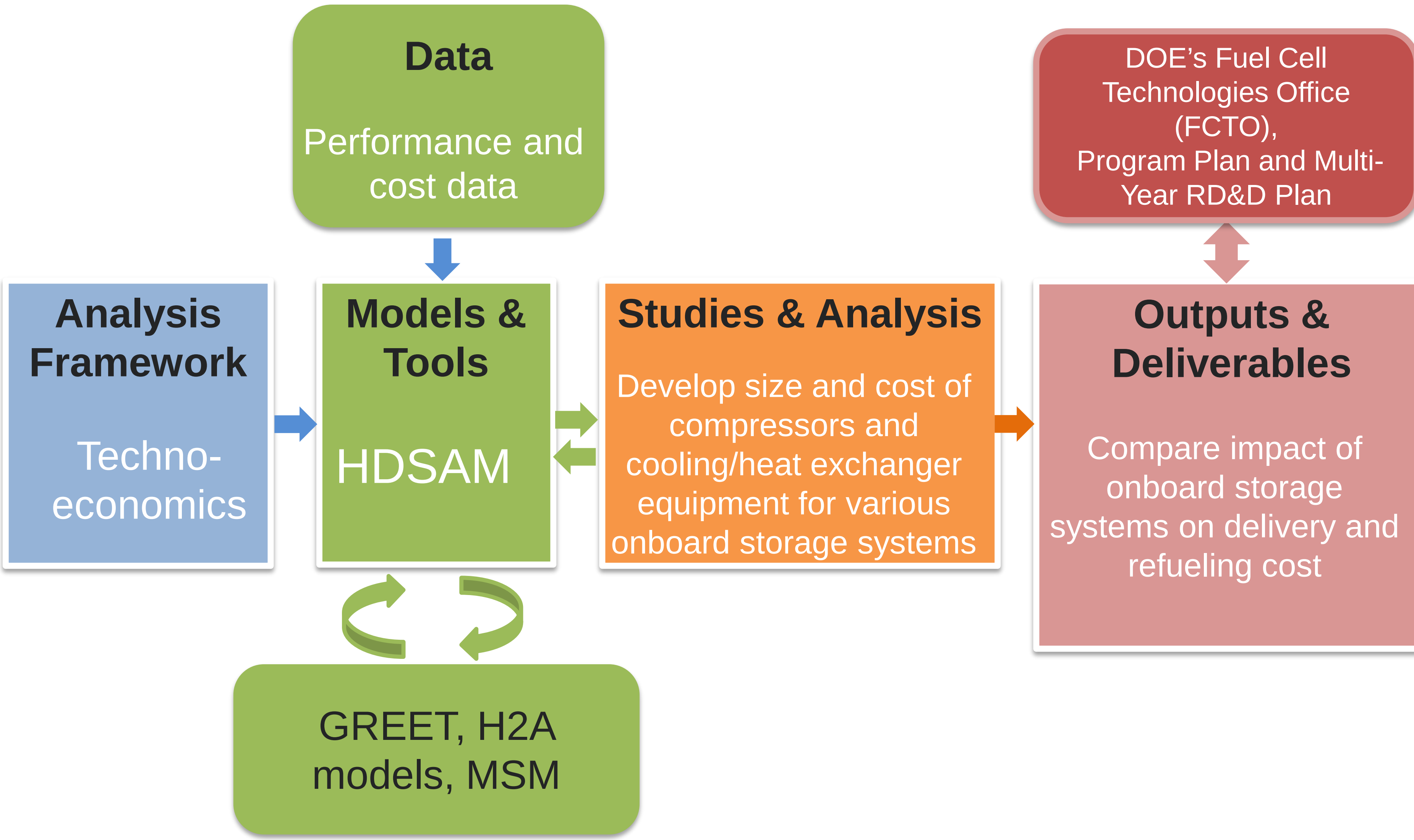
- Sacramento, 50,000 FCEVs (~2030)
- 37 HRS (1000 kg/day capacity)
- Manufacturing volume/learning (20-50% cost reduction)
- Truck delivery (500 bar or LH_2)
- [2016$]

H_2 delivery and production costs are additional (~$5-$8/kg)

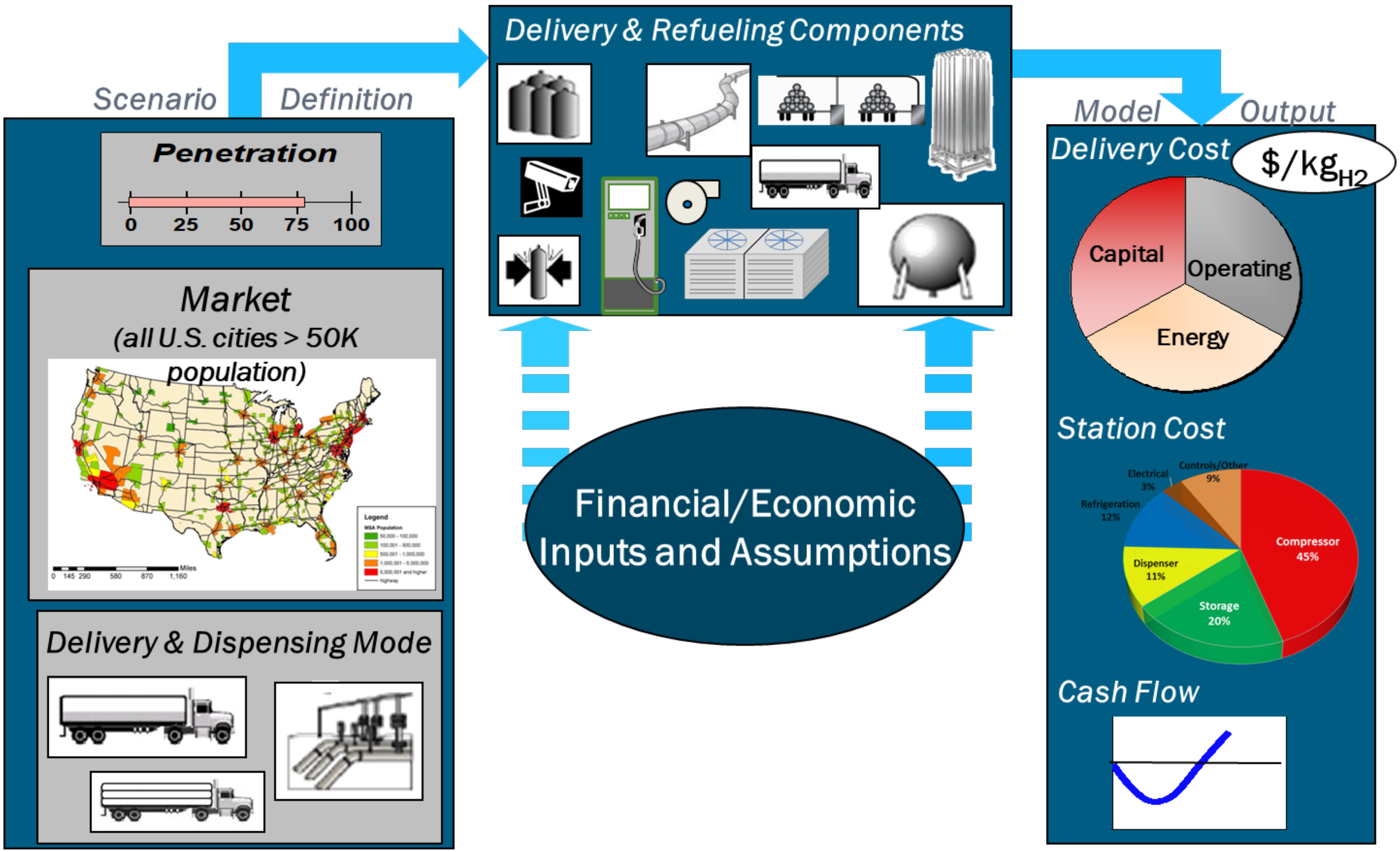


Dispensing P & T strongly impact refueling cost

Impact of onboard storage system on delivery and refueling cost – Relevance/Approach



Develop new delivery and refueling pathways in HDSAM for onboard systems – Approach

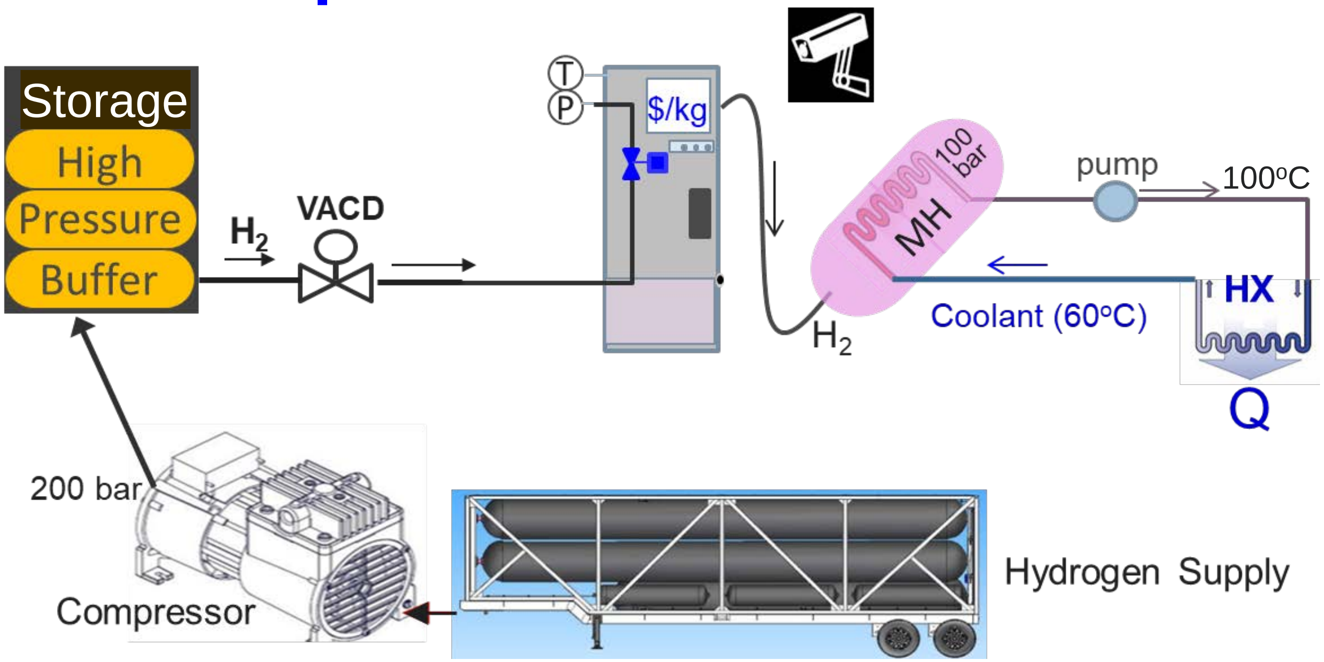


https://hdsam.es.anl.gov/index.php?content=hdsam

HDSAM = Hydrogen Delivery Scenario Analysis Model

Low-Pressure, Near or Above Ambient Temperature Refueling
(Material Storage: MH and Sorbents)

Example of low P, near ambient T refueling: Metal Hydride – Accomplishment



- Examine thermolytic, reversible metal hydride (MH)

  $M + x/2\ H_2 \rightleftarrows MH_x + Q$ (exothermic charging)

  - Refueling equipment must deliver hydrogen (for 100 bar, 300K fills) <u>and</u> remove heat of adsorption (Q) and heat of compression

- Material storage recharges at ~constant pressure, P_{eq}

Low-P, Near/above Ambient T: Prior Results and Context – Accomplishment

- Objective: Compare levelized refueling cost for low-P, near ambient T onboard to 700 bar baseline
  - H_2 delivery and production costs are additional (~$5-$8/kg)
- Prior Results:
  - Constraints and van't Hoff eqn. imply ΔH is 27-41 kJ/mol-H2
  - Defined two bracketing cases via the literature

Case	ΔH	Peak Heat [MW]	Coolant Temperature		P [MPa]
			out, °C	in, °C	
Low T, Low ΔH	28	0.6	100	60	10
High T, High ΔH	47 37	1.1 0.5	168 148	130 130	14

  - Cooling against ambient with air cooled HX (ACHX) is feasible
  - Cooling fluid ΔT limited to ~30-40K, else will impair charging kinetics
    - ✓ Heat duty must be met with coolant mass rate

Low-P, Near Ambient T: New Results – Accomplishment

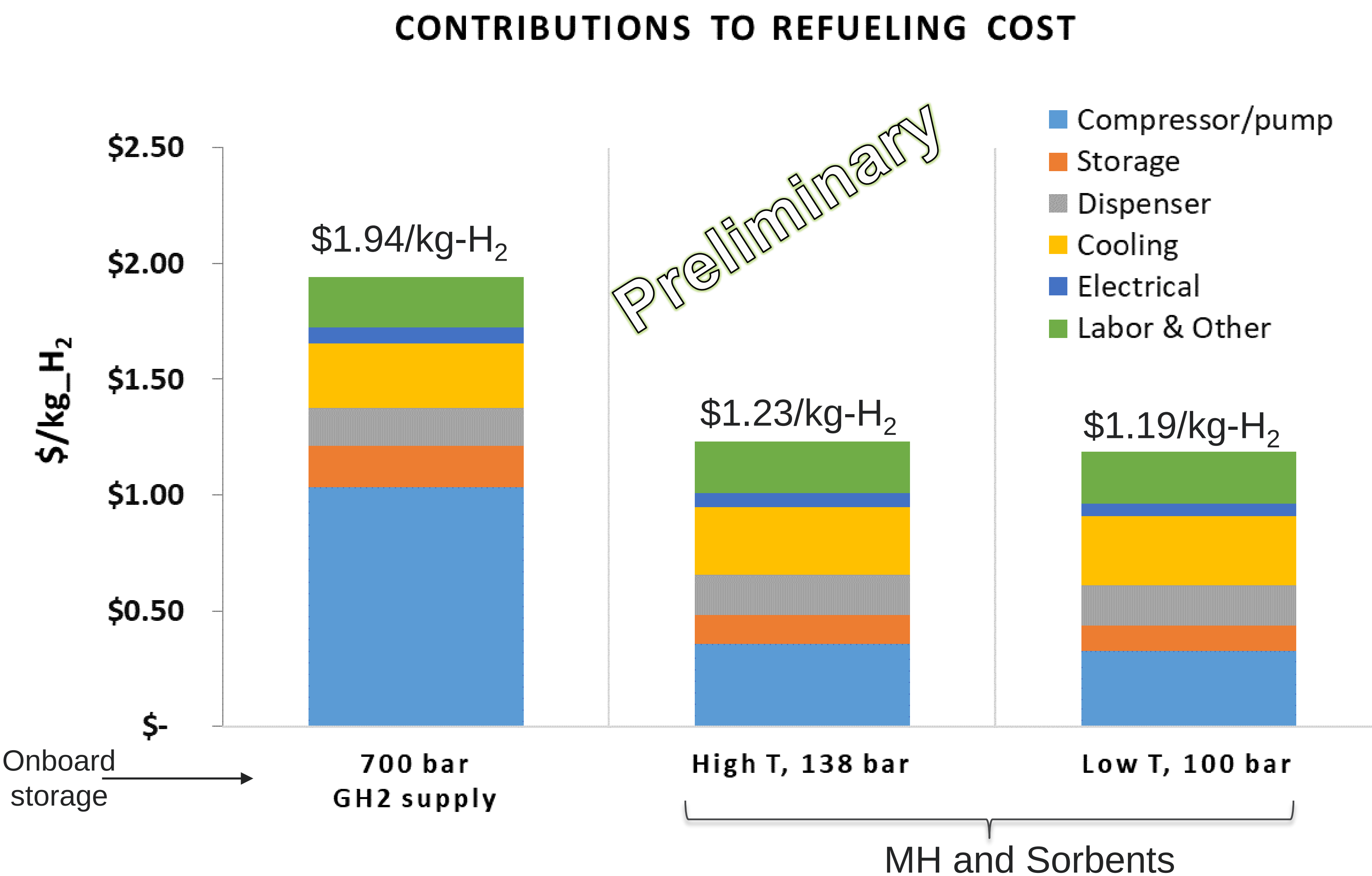
- Progress since last reporting:
  - Validated ACHX costs via two vendor quotes
  - Included four new pathways in HDSAM
  - Conducted sensitivity analysis
  - Documented the analysis in a paper (under review)

- Summary of key TEA Inputs:
  - Note: One ACHX per dispenser, 3 dispensers per station

Scenario	H_2 fill pressure, bar	ACHX cost, $2018	Pump cost, $2018 [a]	ACHX Fan Power, kW	Circulation Power, kW
Low ΔH	100	52,000	6,500	5.1	1.3
High ΔH	138	51,000	7,700	4.4	7.4

[a] Adjusted to 2018 from 1998 via the CEPCI. Uninstalled cost. Installation factor = 2

Low-P, Near Ambient T: MH and sorbents – Accomplishment



Low-pressure, near ambient temperature material storage reduce HRS cost

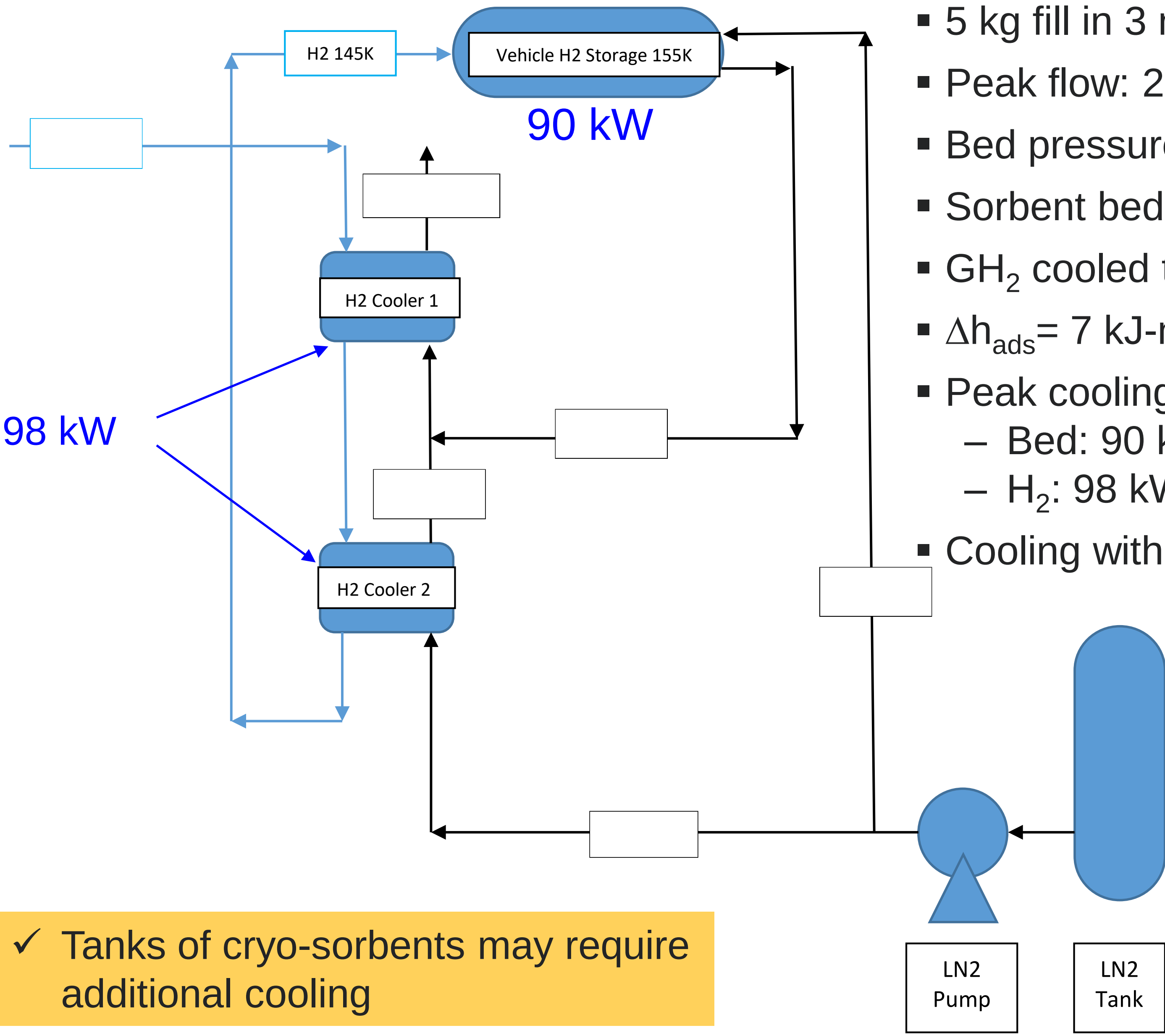
Low-P, Near Ambient T: Sensitivity Analysis – Accomplishment

Parameter	Parameter Value Low	Parameter Value Baseline	Parameter Value High	Refueling Cost, $/kg Low	Refueling Cost, $/kg Baseline	Refueling Cost, $/kg High
ACHX area, sf	150	300	600	$1.21	$1.23	$1.27
ACHX fan power, kW	2.2	4.4	8.8	$1.21	$1.23	$1.26
Coolant pump power, kW	3.7	7.4	14.7	$1.23	$1.23	$1.24
ACHX fan runtime, hr/day	8	18	24	$1.21	$1.23	$1.24
Fill pressure, MPa	10	13.8	20	$1.19	$1.23	$1.28
Attendants, # of people	0	0.46	1	$1.08	$1.23	$1.40

- Large variations of most key parameters had little effect
  - ACHX small vs. chemical processing industry
  - Cooling power small vs. compressor power → low sensitivity
- The largest cost increase occurs if self-service is impractical
  - R&D needed to develop manageable interconnect for hot coolant lines and H_2

Low-Pressure, LN_2 Temperature Refueling (Cryo-sorbents)

Cooling System for Cryo-Sorbent Refueling with GH_2 – Accomplishment



- 5 kg fill in 3 minutes
- Peak flow: 2.7 kg/min
- Bed pressure 5 bar → 100 bar
- Sorbent bed temp. 300K → 155K
- GH_2 cooled to 145K
- Δh_{ads}= 7 kJ-mol-H_2
- Peak cooling loads:
  - Bed: 90 kW
  - H_2: 98 kW
- Cooling with LN_2

✓ Tanks of cryo-sorbents may require additional cooling

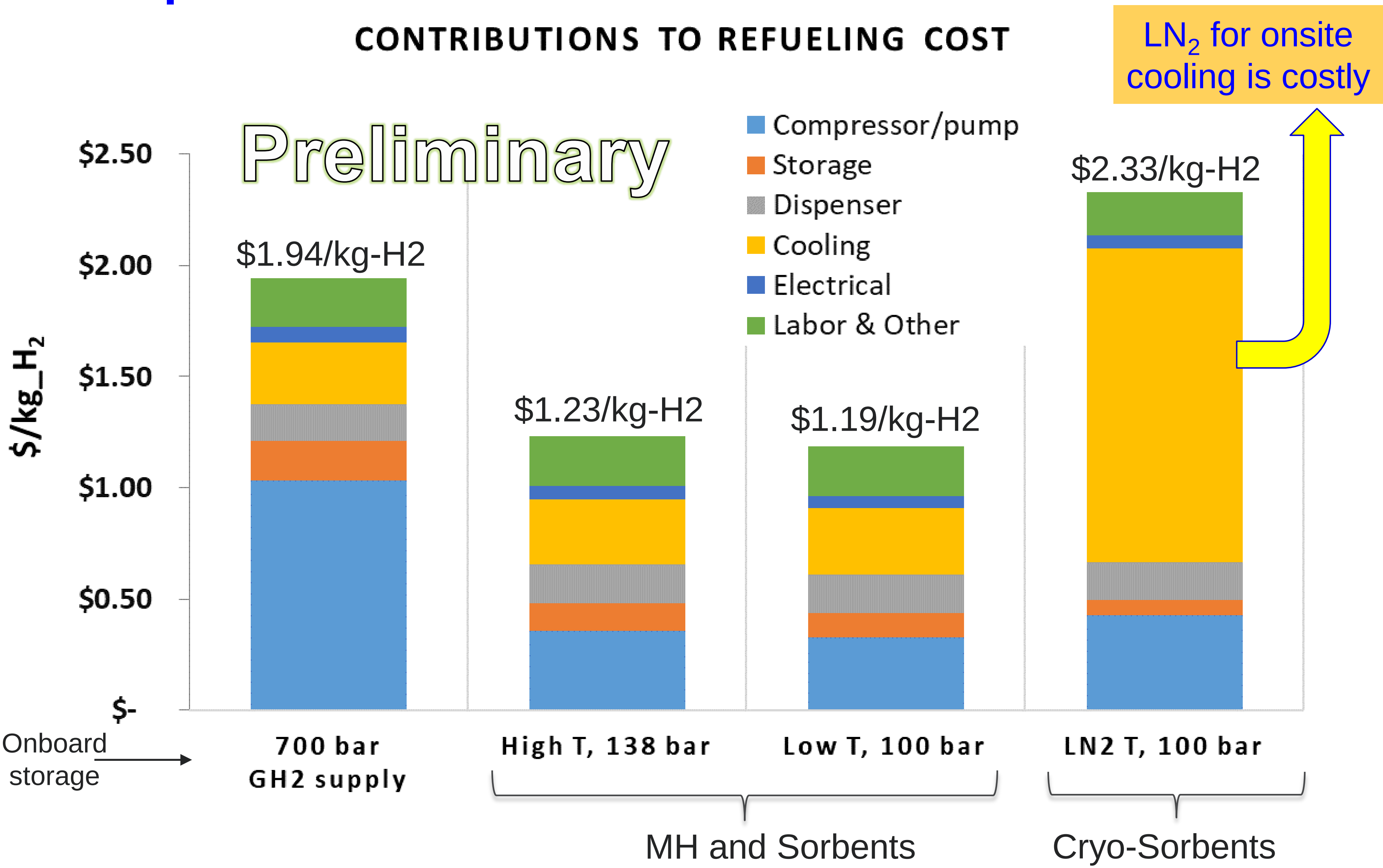
Argonne NATIONAL LABORATORY

Low P, LN2 temperature refueling case – Accomplishment

Scenario	Heat Duty	H_2 T_{inlet}	H_2 T_{outlet}	HX UA	Uninstalled HX cost (per dispenser)
	[kW]	[K]	[K]	[W/K]	[$]
Cooler 1	94	300	151	4360	61,000
Cooler 2	4	151	145	280	4,000

- LN_2 delivered to station in volume (~5000 gallons) at $0.3/gallon ($0.1/kg_{LN2})
- 11 kg (3.6 gallon) of LN_2 per kg of H_2 dispensed → 55 kg (18 gallon) LN_2 per vehicle
- Daily LN_2 use = 8,800 kg (2900 gallons) of LN_2 for 800 kg_{H2} dispensed per day
- LN_2 tank (7250 gallons) cost (uninstalled) = $178,000 ($140,000 future mid volume)
- LN_2 pump capacity = 75 kg/min, 1 kW motor
- Pump cost (uninstalled) = $15,000 (per dispenser, mid volume)
- HX cost is today low volume (uninstalled), mid volume @79%, installation factor = 1.35
- 30m VJ piping costs $37,000 (mid volume production factor = 0.79), including 1.9 installation cost factor. Four VJ valves are $10,000, installed.

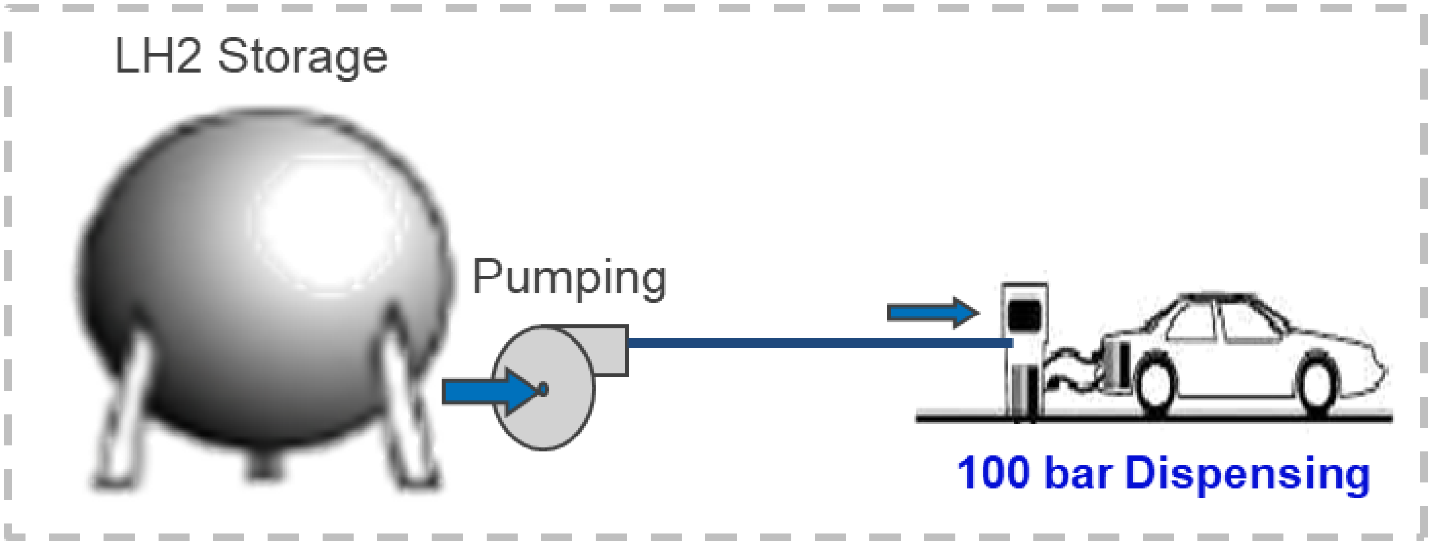
Refueling cost with tube trailer gaseous deliveries – Accomplishment



LH_2 Temperature Refueling

1. Low-Pressure, Cryo-Sorbents
2. Cryo-compressed (CcH_2)
3. 700 bar Gaseous

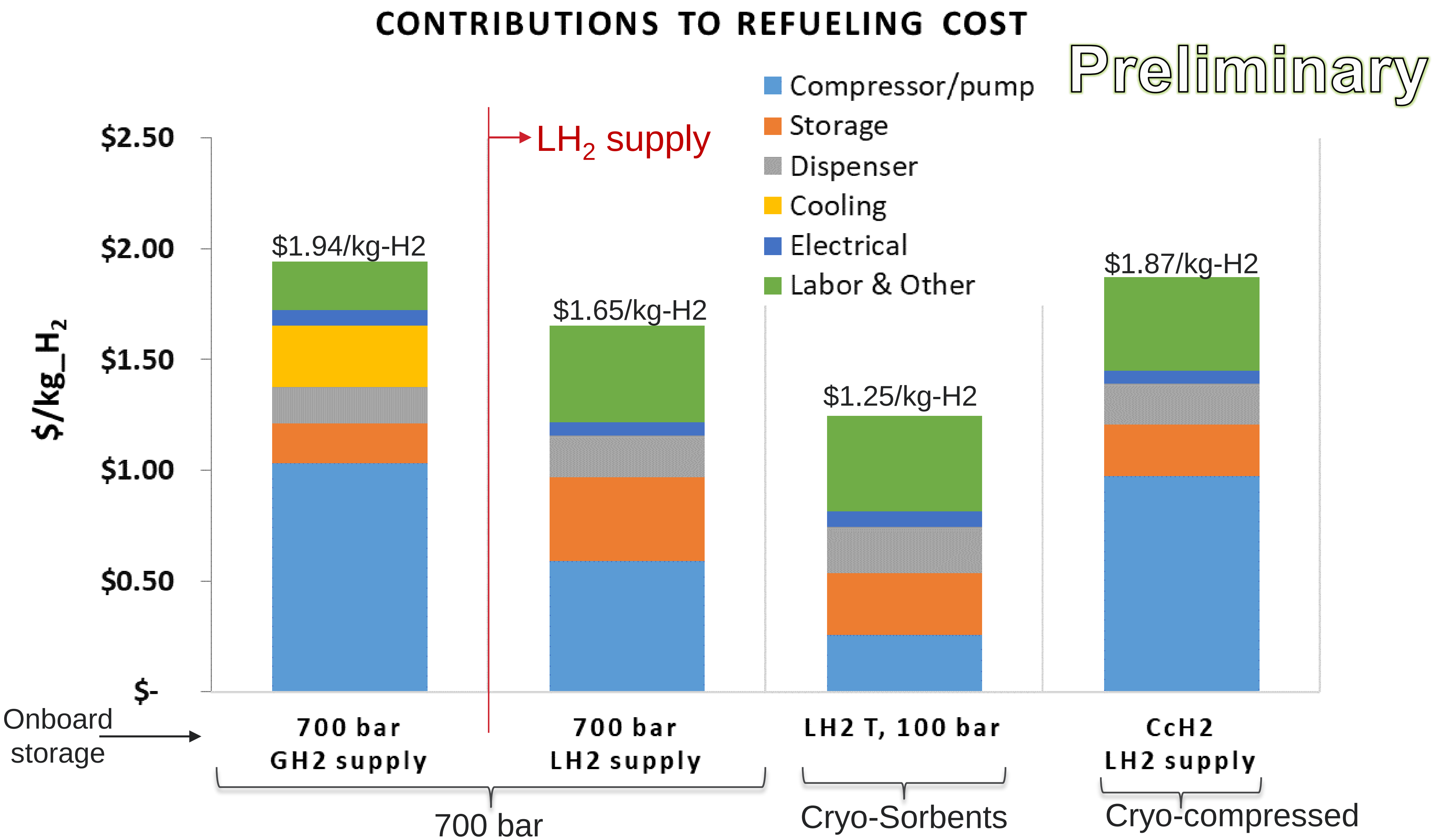
Example of low P, LH_2 temperature refueling: Cryo-sorbents – Accomplishment



- 5 kg fill in 3 minutes
- Bed pressure 5 bar → 100 bar
- Sorbent bed temp. 300K → 155K
- Dispensed LH_2 provides cooling

✓ Similar configuration as cryo-compressed (CcH_2)
✓ Tanks of cryo-sorbents may require additional cooling

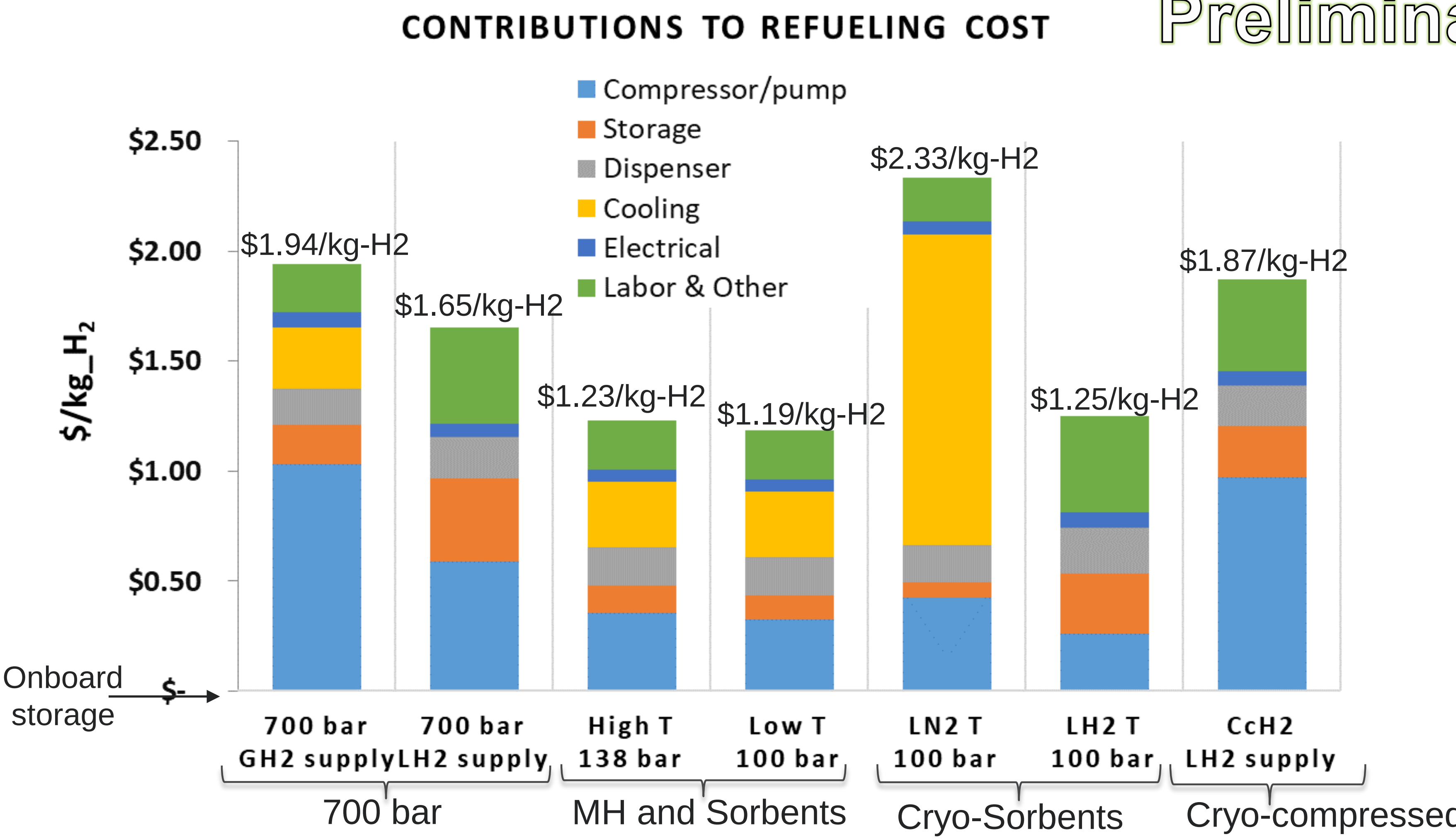
Refueling cost with liquid Hydrogen (LH_2) deliveries – Accomplishment



- ✓ LH_2 fueling of cryo-sorbents is attractive if no additional cooling is required
- ✓ CcH_2 can be attractive if cost of high-pressure cryo-pump is reduced

Summary of levelized HRS cost contribution for different dispensing P and T – Accomplishment

Preliminary



- ✓ Low-pressure, near ambient temperature material storage reduce HRS cost
- ✓ LH_2 is most versatile, allowing all fueling options, including cryogenic T

Summary – Accomplishment

- Evaluated impact of onboard hydrogen storage options on refueling cost
  - Metal Hydride (MH) → 100 bar, near ambient temperature
  - Sorbents → 100 bar, near ambient temperature
  - Cryo-sorbents → 100 bar, 145K, and near LH_2 temperature
  - Cryo-compressed Hydrogen → 350 bar, 35K
  - ✓ Compare to 700 bar refueling (both liquid and gaseous supply)

- MH and sorbents near ambient temperature provides the largest potential for refueling cost reduction
  - Cost reduction ~40%
  - Most of the cost reduction is attributed to low refueling pressure

- Cryo-sorbents using LN_2 shows increase in cost of refueling despite low refueling pressure
  - Most of the cost increase is attributed to LN_2 onsite cooling
  - Cost of delivered LN_2 adds $1/$kg_{H2}$

- Liquid hydrogen is most versatile, allowing all fueling options
  - especially those requiring low temperature

Collaborations and Acknowledgments

- Daryl Brown of Energy Technology Analysis supported the sorbents pathway analysis
- Mike Veenstra, Ford Motor Company, provided technical information and general guidance and support
- Jesse Adams (DOE) provided technical information and general guidance and support
- Terry Johnson of Sandia National Laboratory provided performance data for MH systems
- Kriston Brooks and Ewa Ronnebro of Pacific Northwest National Laboratory provided performance data for MH systems
- David Tamburello of Savannah River National Laboratory provided performance data for sorbent systems
- U.S.DRIVE Delivery and Storage Tech Teams

Future Work

- Expand system boundary to include delivery + refueling cost for consistent comparison
- Conduct energy and emissions analysis (life cycle)
- Review new pathways in HDSAM
  - Conduct independent model review by subject matter experts
  - Release updated HDSAM with new pathways
- Document data and analysis in peer-reviewed publication
- Conduct similar analysis for Medium- and heavy-duty vehicles

Project Summary

- **Relevance**: On-board hydrogen storage systems can have large impact on refueling cost of fuel cell vehicles
- **Approach**: Develop new delivery and refueling pathways in HDSAM for onboard systems
- **Collaborations**: Collaborated with consultants and experts from other national labs (ETA, LLNL) and sought data and guidance from experts (industries and across US DRIVE technical teams)
- **Technical accomplishments and progress**:
  – Evaluated impact of material storage (MH and sorbents) on refueling cost of fuel cell vehicles
  – Onboard material storage charged near ambient temperature provides the largest potential for refueling cost reduction compared to 700 bar refueling (~$1/kg$_{H2}$)
  – Cryo-sorbents show increase in cost of refueling when LN_2 is used for onsite cooling, while LH_2 charging of cryo-sorbents show much lower fueling cost
  – Liquid hydrogen is most versatile, allowing all fueling options, especially those requiring low temperature fueling
  – Implemented new material fueling pathways in HDSAM
- **Future Research**:
  – Expand system boundary to include delivery + refueling cost for consistent comparison
  – Conduct energy and emissions analysis (life cycle)
  – Review new pathways in HDSAM
  – Conduct independent model review by subject matter experts
  – Release updated HDSAM with new pathways
  – Document data and analysis in peer-reviewed publication
  – Conduct similar analysis for Medium- and heavy-duty vehicles

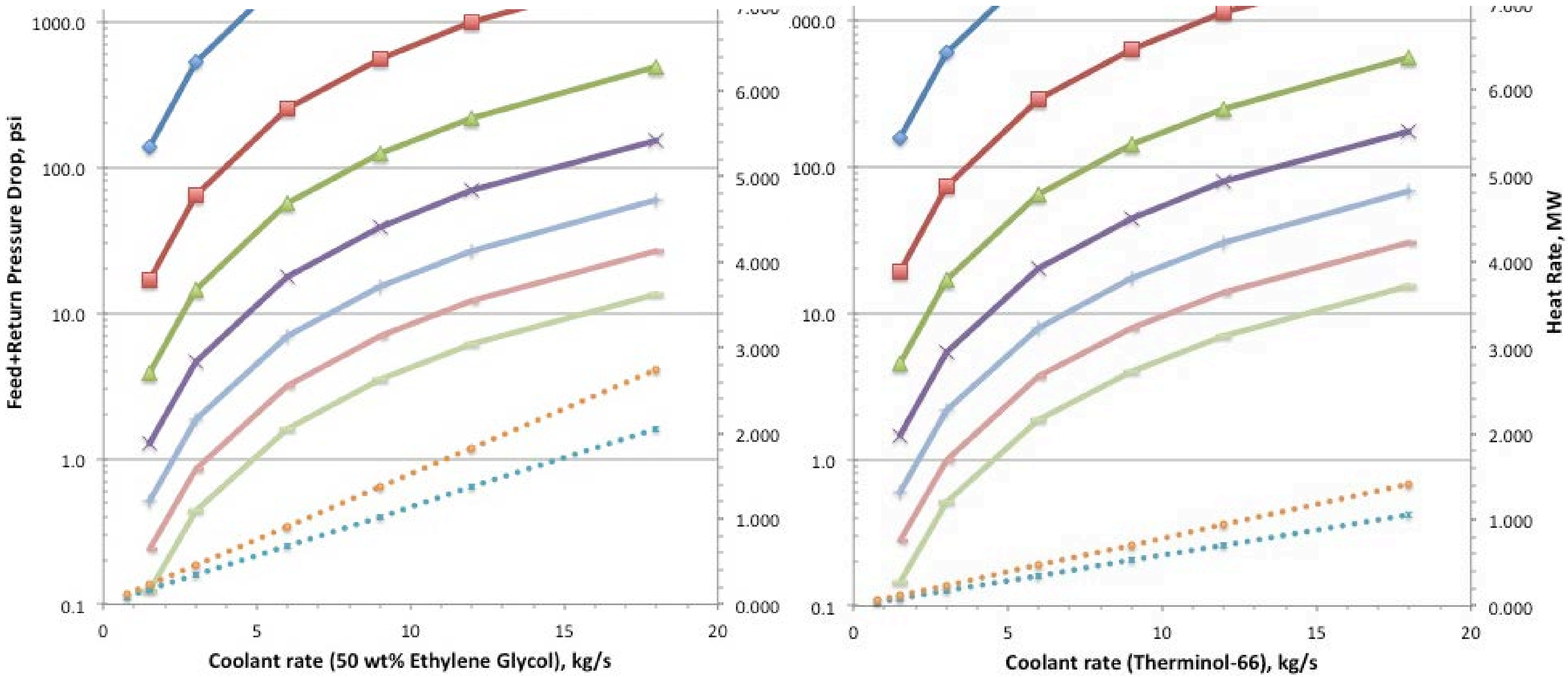
aelgowainy@anl.gov

Backup Slides

Acronyms

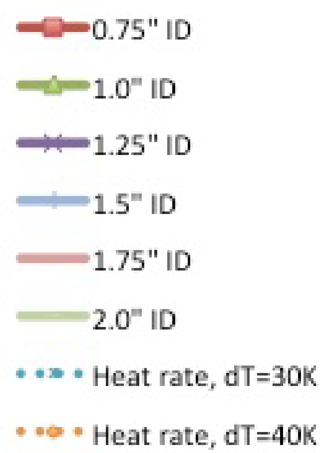
- AMR: Annual Merit Review
- ANL: Argonne National Laboratory
- CA: California
- CcH_2: Cryo-compressed
- CF: Carbon Fiber
- Cp: Specific heat at constant pressure
- DOE: Department of Energy
- ETA: Energy Technology Analysis
- FCEV: Fuel Cell Electric Vehicle
- FCTO: Fuel Cell Technologies Office
- FY: Fiscal Year
- GH_2: Gaseous Hydrogen
- GN_2: Gaseous Nitrogen
- GREET: Greenhouse gases, Regulated Emissions, and Energy use in Transportation
- H: Enthalpy
- Δh_{ads}: Enthalpy of Adsorption
- H_2: Hydrogen
- H2A: Hydrogen Analysis
- HDSAM: Hydrogen Delivery Scenario Analysis Model
- HP: Horse Power
- HRS: Hydrogen Refueling Station
- HX: Heat Exchanger
- ID: Inner Diameter
- LxW: Length x Width
- LH_2: Liquid Hydrogen
- LN_2: Liquid Nitrogen
- m^o: Mass Flow Rate
- MH: Metal Hydride
- MLVI: Multi-Layer Vacuum Insulation
- MOF: Metal Organic Framework
- MSM: Macro-System Model
- P: Pressure
- RD&D: Research, Development, and Demonstration
- S: Entropy
- T: Temperature
- TEA: Techno-Economic Analysis
- ΔT: temperature difference
- US: United States
- US eq. gal: U.S. equivalent gallon
- US DRIVE: U.S. Driving Research and Innovation for Vehicle efficiency and Energy sustainability
- VACD: Variable Area Control Device
- WTW: Well-to-Wheels

Low-P, Near Ambient T: Prior Results and Context



- Coolant supply and return lines:
  - 1”-1.25” ID (low-T, 0.6 MW) or ~1.75”-2.00” ID (Hight-T, 1 MW)
  - Otherwise, large pressure drop
  - Bulky interconnect seems likely

Station attendant may be required



Low-P, Near Ambient T: Discussion – Accomplishment

- Higher-enthalpy materials have larger on-board parasitic losses at station:
  - Required much higher coolant rates, larger pressure drops
  - But ΔT to transfer heat to ambient was more favorable

- This project did not evaluate change in vehicle cost, material storage vs. 700-bar

- ACHX will mix coolant between vehicles
  - Did not consider costs for filtration / purification
  - Opportunity to reduce ACHX cost (scale)

Low P, LN_2 temperature refueling case – Approach

- Objective: Determine impact of low P, LN_2 temperature refueling on levelized refueling cost of cryo-sorbents
  - Compare to refueling baseline 700 bar onboard storage

- Approach:
  - Define refueling conditions (e.g., P, T) for sorbent charging scenarios
  - Determine practical operation constraints
  - Determine and size major items of refueling equipment (e.g., LN_2, HX)
  - Acquire cost of components
  - Implement in HDSAM
  - Calculate and compare levelized refueling cost for baseline and sorbent storage scenarios on a consistent basis

Developed GH_2 and LH_2 Pathways for Fueling Sorbent Storage Onboard Vehicle – Accomplishment

- Developed new sorbent tab in HDSAM.
- Fueling onboard sorbent storage with GH_2 requires an additional system for cooling sorbent bed and hydrogen gas.
- Delivered LN_2 used for cooling GH_2 supply.
- Onboard sorbent storage may be directly fueled with LH_2. Evaporating LH_2 is assumed to simultaneously cool sorbent bed/tank and accommodates heat of adsorption.

Cost Estimating Data Sources – Accomplishment

- Acquired vendor estimates for hydrogen cooling heat exchangers.
- Acquired vendor estimates for LN_2 delivered in bulk by truck.
- Used same $\$/m^3$ for LN_2 storage vessel as for existing LH_2 storage vessel cost model.
- LN_2 pump cost developed from vendor estimates.
- Vendor data used for vacuum-jacketed (VJ) piping costs.