2018 DOE Hydrogen and Fuel Cells Program
Annual Merit Review

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

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Overview

Timeline

- Start: October 2017
- End: Determined by DOE
- % complete (FY18): 70%

Barriers to Address

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

Budget

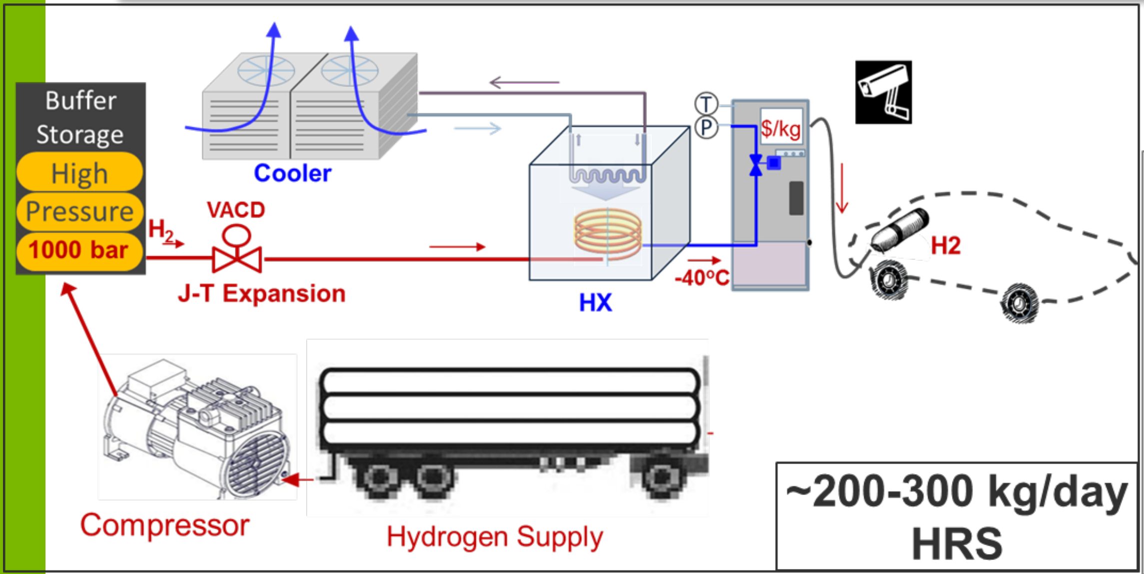
- Funding for FY18: $260K

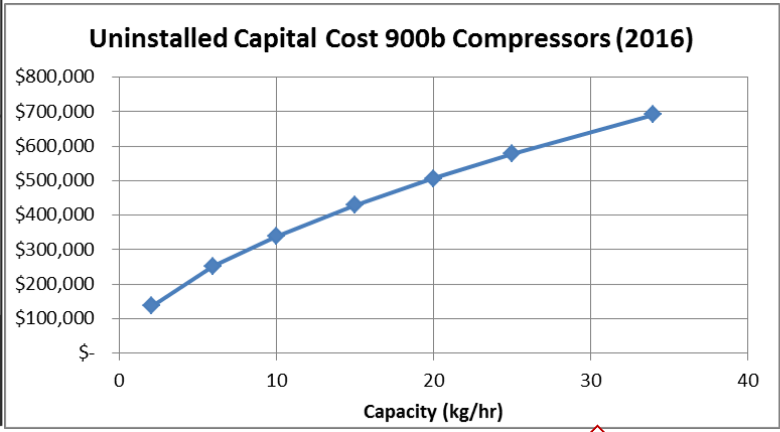
Partners/Collaborators

- U.S.DRIVE: Hydrogen Interface Taskforce (H2IT)
- Lawrence Livermore National Laboratory (LLNL)
- Energy Technology Analysis (ETA)

Relevance/Impact

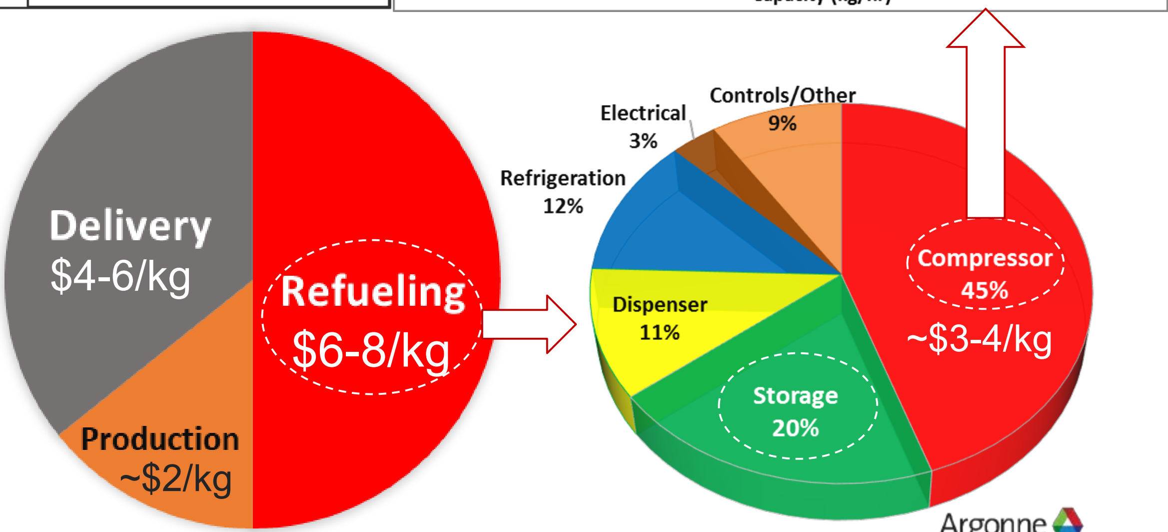
Objective: Evaluate impacts of on-board hydrogen storage systems on delivery and refueling cost





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

Bulk of H_2 cost is in delivery and refueling

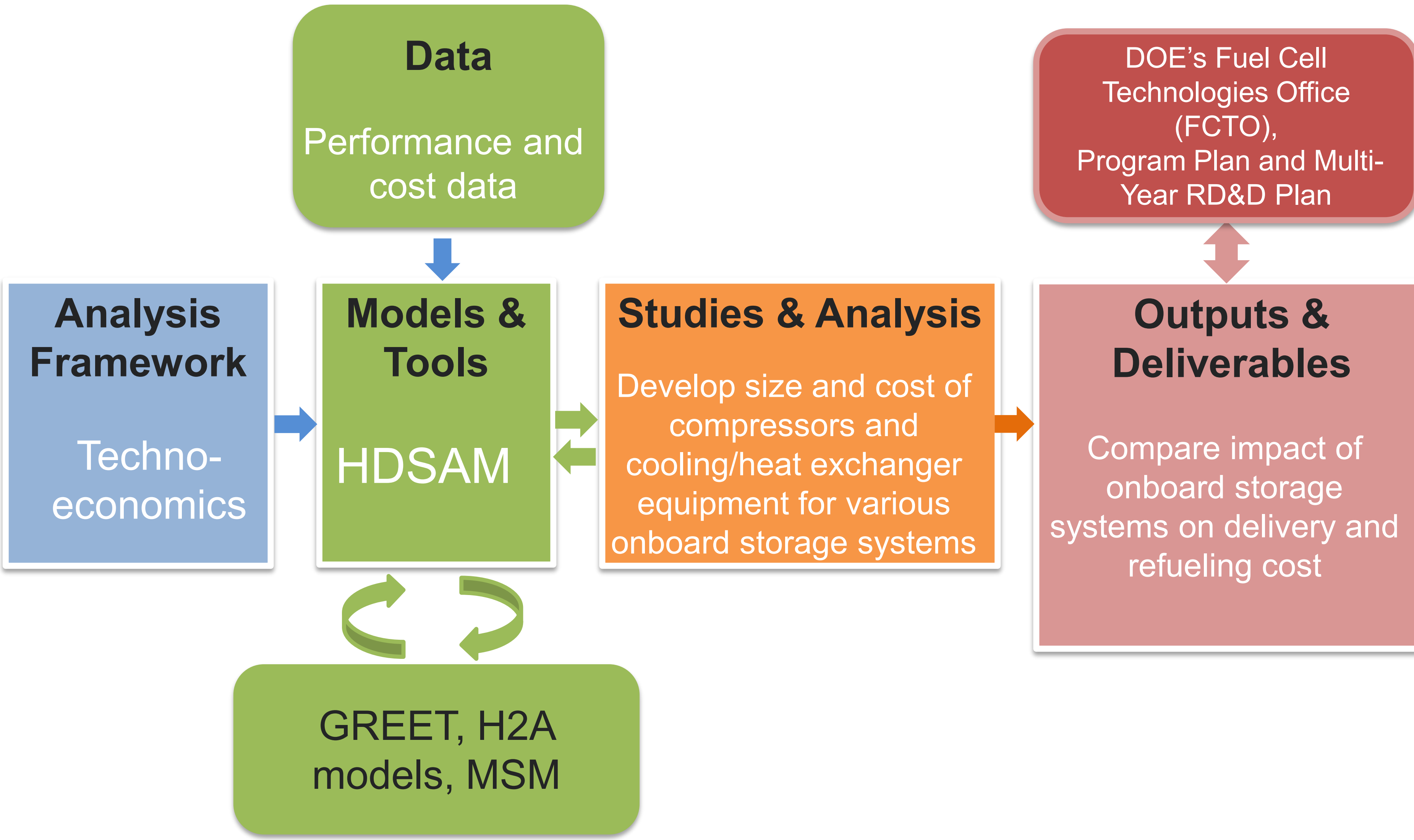


Pathways for consideration – Relevance

- ✓ 700 bar storage/refueling (baseline)
- ✓ Metal Hydride (MH) storage/refueling
- ✓ Metal Organic Framework (MOF-5) storage/refueling
- ✓ Cold Gas storage/refueling
- ❑ Cryo-compressed hydrogen (CcH2) storage/refueling

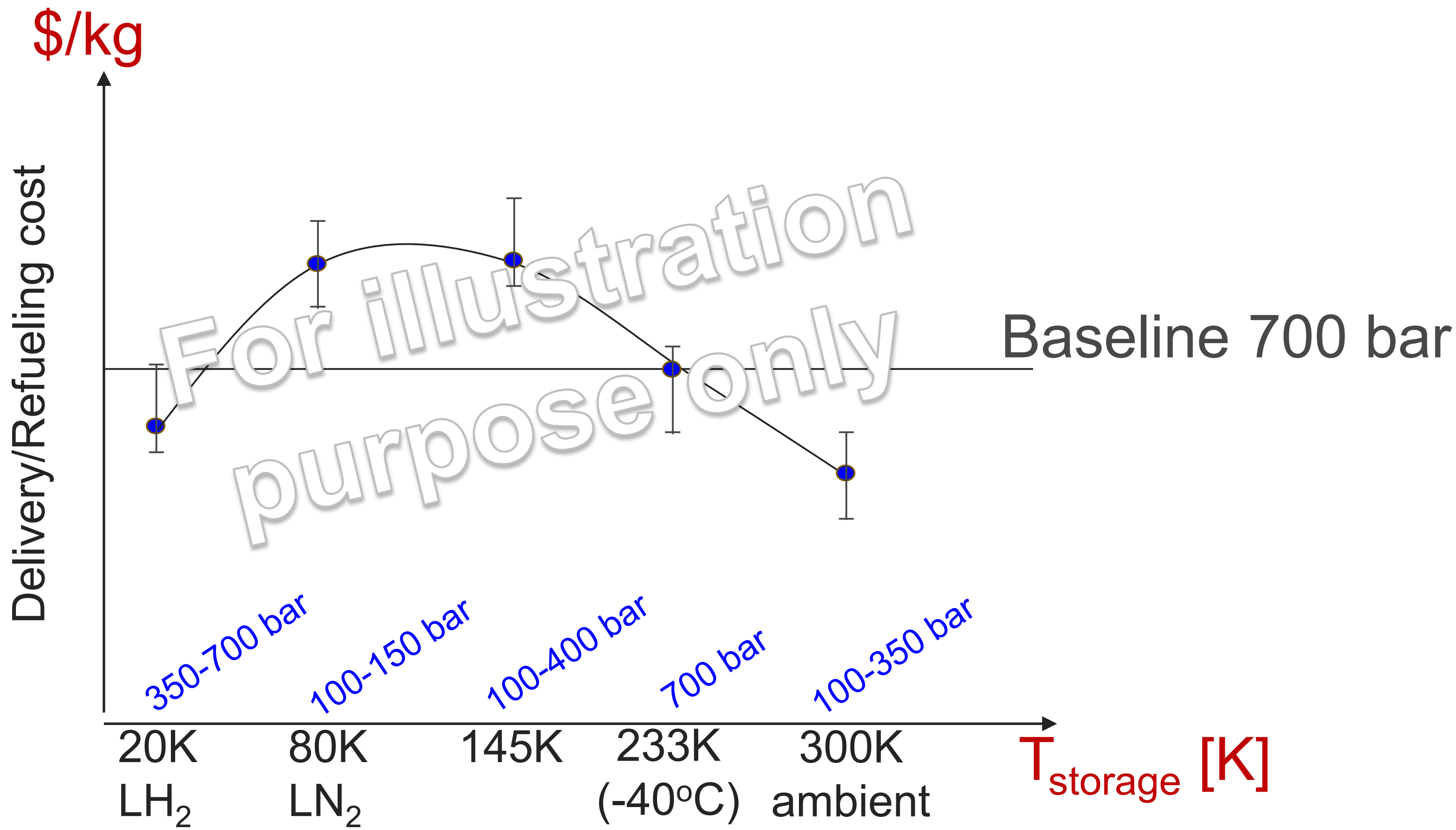
Storage System	System Model Source	Configuration	Operating Temperature	Operating Pressure
700 bar Compressed H2	Baseline	Single Tank CF Overwrap	Ambient (-40 to 85°C)	5 bar to 875 bar
350 bar Cryo-compressed	ANL	Type 3 Tank with MLVI	35 to 93 K	5 to 350 bar
700 bar Cryo-compressed	ANL	Type 3 Tank with MLVI	35 to 123 K	5 to 700 bar
400 bar Cold gas	ANL	Type 4/CF/MLVI	180 to 195 K	5 to 400 bar
100 bar Cryo-Adsorbent cryo-cooled	ANL	MOF-5 within Type 3 Tank with MLVI	145 to 215 K	5 to 100 bar
Metal hydrides	ANL	Reverse engineering material within Type 3 Tank	Ambient (-40 to 120^{o}C)	5 to 100 bar

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



Outcome of Analysis – Approach

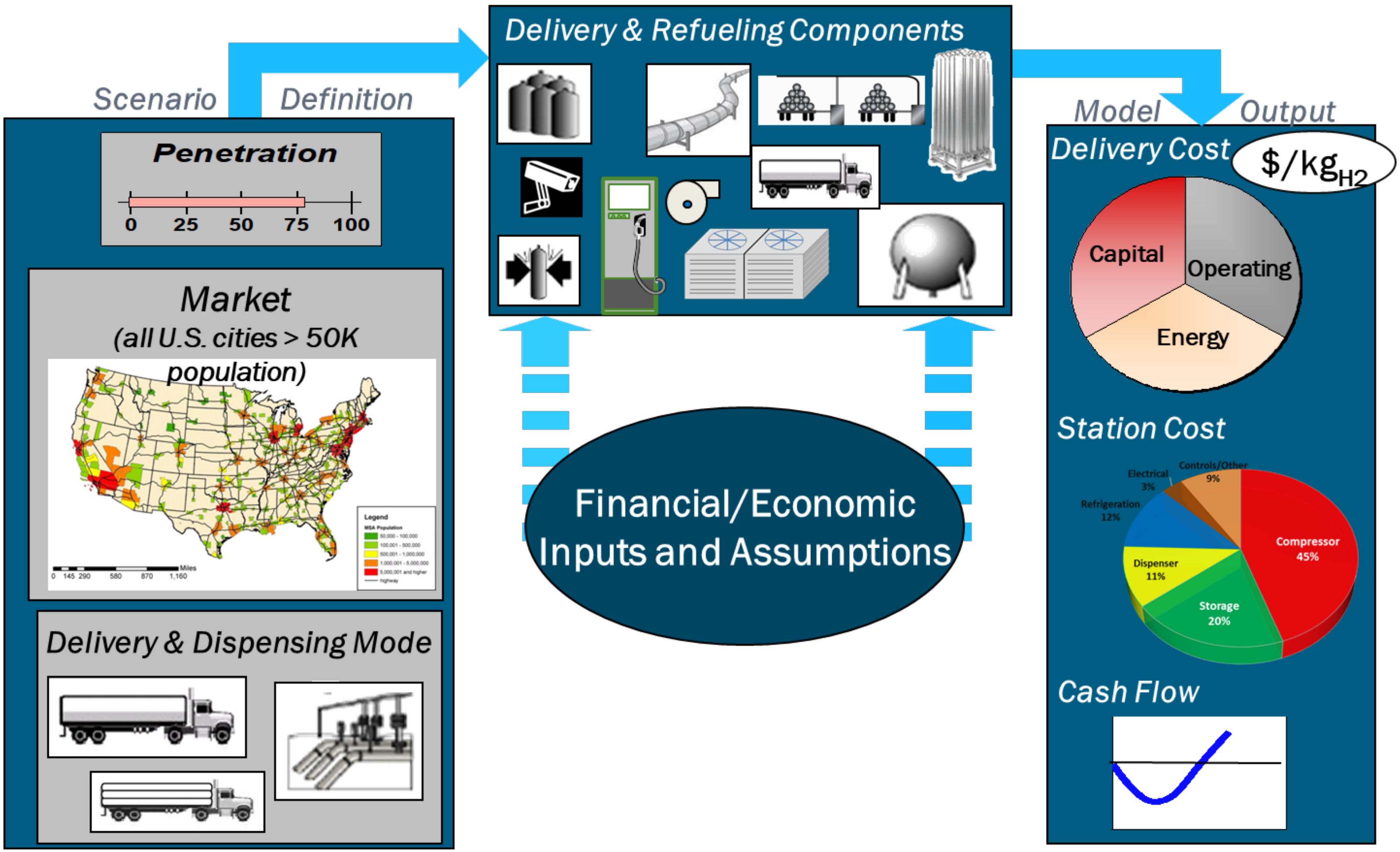
- Compare impact of P-T tradeoffs on hydrogen delivery and refueling cost [$/kg]



Required temperature/pressure for various onboard storage systems

P & T are key for refueling cost

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

Metal Hydride Pathway – Approach

- Thermolytic, reversible metal hydride

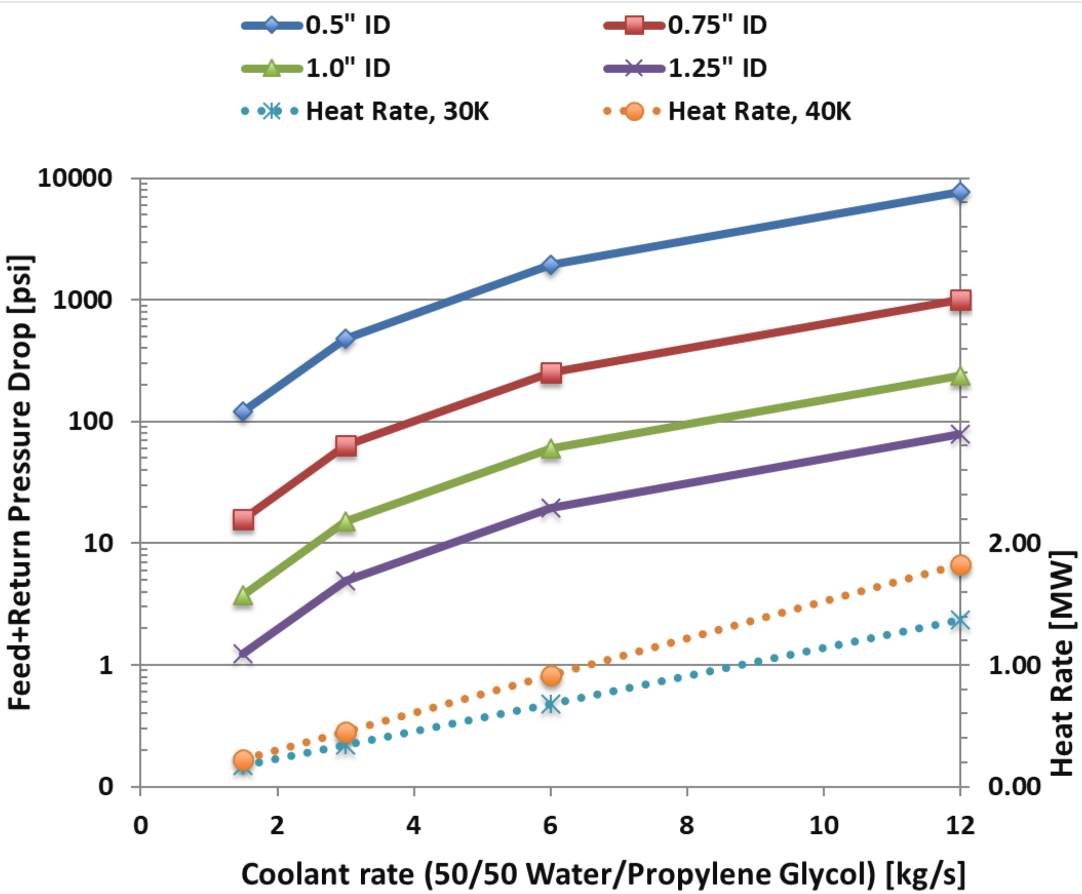
  $$M + x/2\ H_2 \rightleftarrows MH_x + \text{Heat}$$

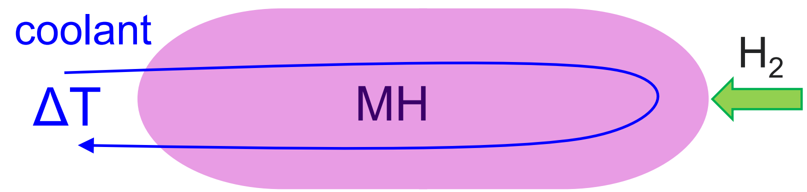
- Exothermic charging, so refueling equipment must deliver hydrogen (100 bar, 300K) and remove heat of adsorption and compression
- Heat of compression is additional 0.1 MW
- Hydriding enthalpy is constrained to 27−41 kJ/mol-H_2

-Average Cooling duty 0.4−0.6 MW for refueling 5 kg H_2 in 3 minutes
-Peak cooling can be 1 MW

Metal Hydride Pathway: Kinetics – Accomplishment

- Charging rate is affected if MH is either too cold or too hot
  - Must constrain ΔT → 30−40K
    - ✓ 1 MW cooling via dm/dt and Cp rather than by ΔT





- Coolant supply and return lines >1” ID
  - Otherwise, large pressure drop
  - Bulky interconnect seems unavoidable
  - Hot fluid with enough pressure to spray

Station attendant may be required

Developed HX Design for Two Metal Hydride – Accomplishment

(1) Low-temperature, low-enthalpy
(2) High-temperature, high-enthalpy

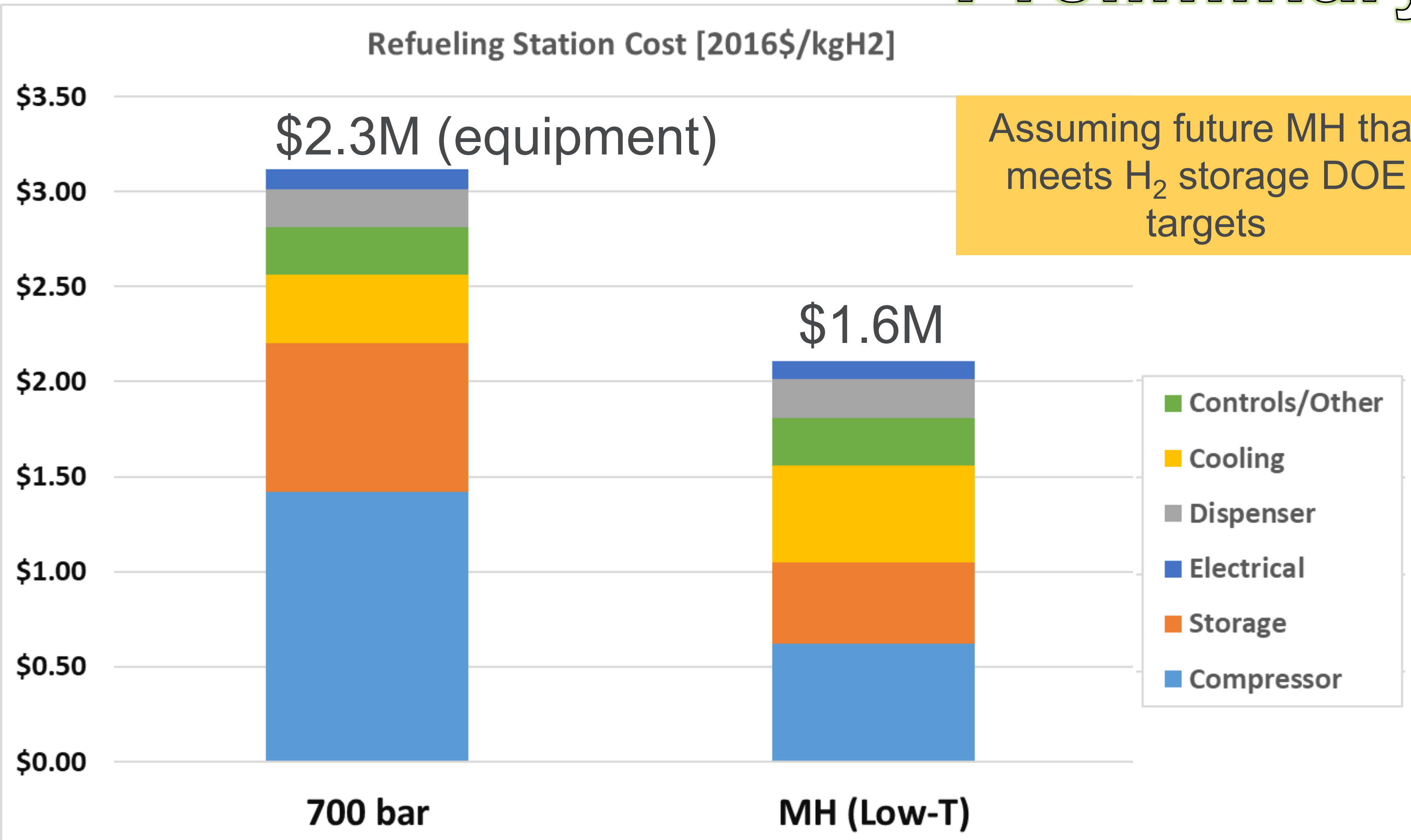
Scenario	Heat Duty	Coolant T_{inlet}	Coolant T_{outlet}	Coolant m°	HX LxW	HX Weight	Fan Power	Pump Power	HX Cost
	MW	°C	°C	Kg/s	ft	lb	HP	HP	$
Low-T, Low-H	0.6	100	61	3.6	14x13	12,000	8	2	52,000
High-T, High-H	1.1	168	129	10.3	14x5	2,700	3	9	16,000

Preliminary

- HX design using Aspen
- Ambient Temperature 38°C
- Tube-fin HX, tube diameter = 0.75”
- Steel tubes/Aluminum fins, G-fins, 14 FPI
- Low-T: 50/50 (wt%) propylene glycol/water coolant; 6 tube rows, 6 passes
- High-T: 92/8 (wt%) ethylene glycol/water coolant; 4 tube rows, 4 passes
- Low-T: HX area 19,000 ft^2, air face velocity = 6 ft/s
- High-T: HX area 3,200 ft^2, air face velocity = 12 ft/s
- HX cost is uninstalled, installation factor = 2

Metal Hydride Pathway: Refueling Cost – Accomplishment

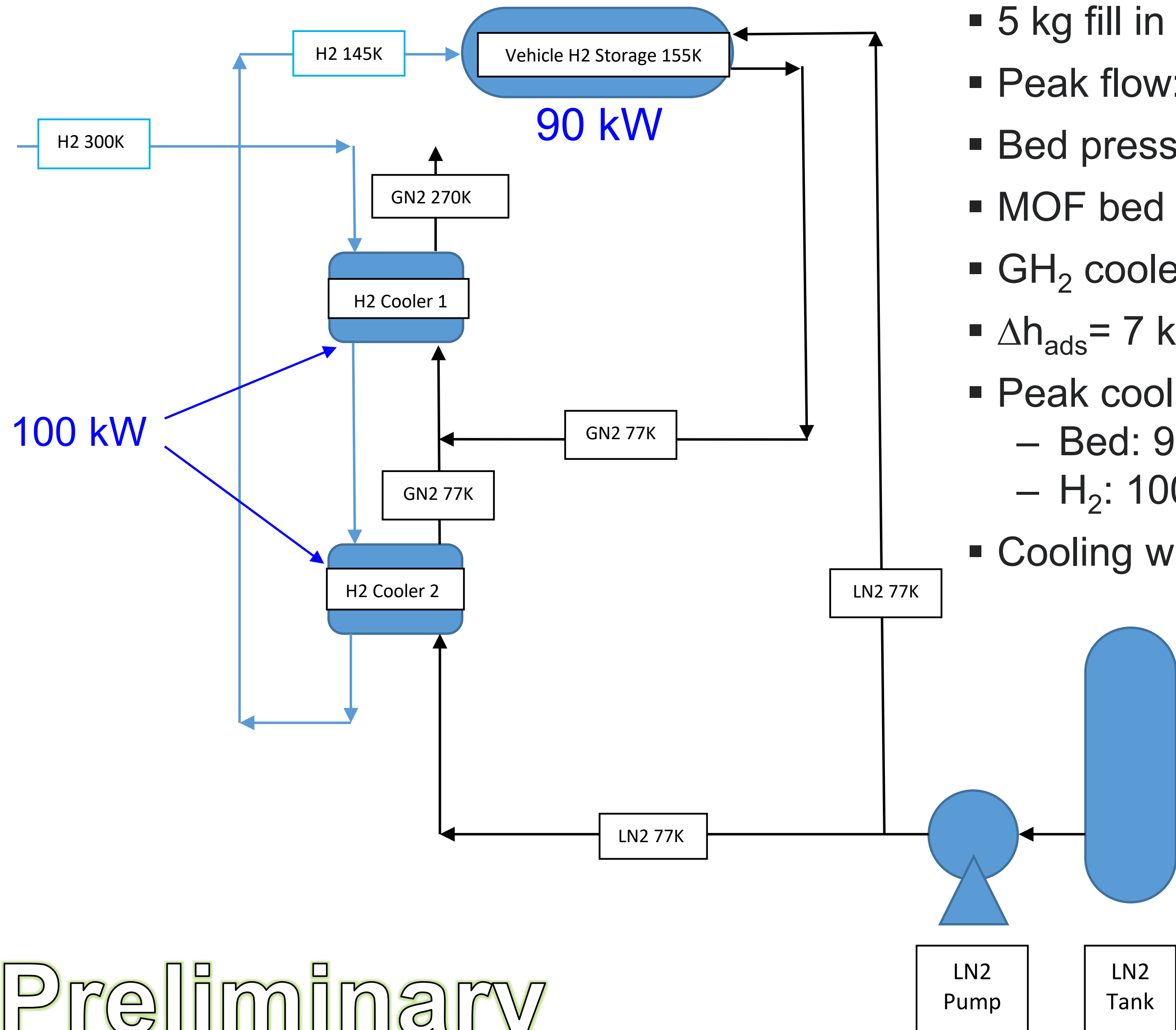
Preliminary



Assuming future MH that meets H_2 storage DOE targets

1000 kg/day station Capacity, 0.8 Capacity factor, 20bar H_2 supply, 4 dispensers

Designed H_2 Cooling System for MOF Refueling – Accomplishment



- 5 kg fill in 3 minutes
- Peak flow: 2.6 kg/min
- Bed pressure 5 bar → 100 bar
- MOF bed temp. 300K → 155K
- GH_2 cooled to 145K
- Δh_{ads}= 7 kJ-mol-H_2
- Peak cooling loads:
  - Bed: 90 kW
  - H_2: 100 kW
- Cooling with LN_2

Preliminary

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Estimated HX Cost for MOF Refueling – Accomplishment

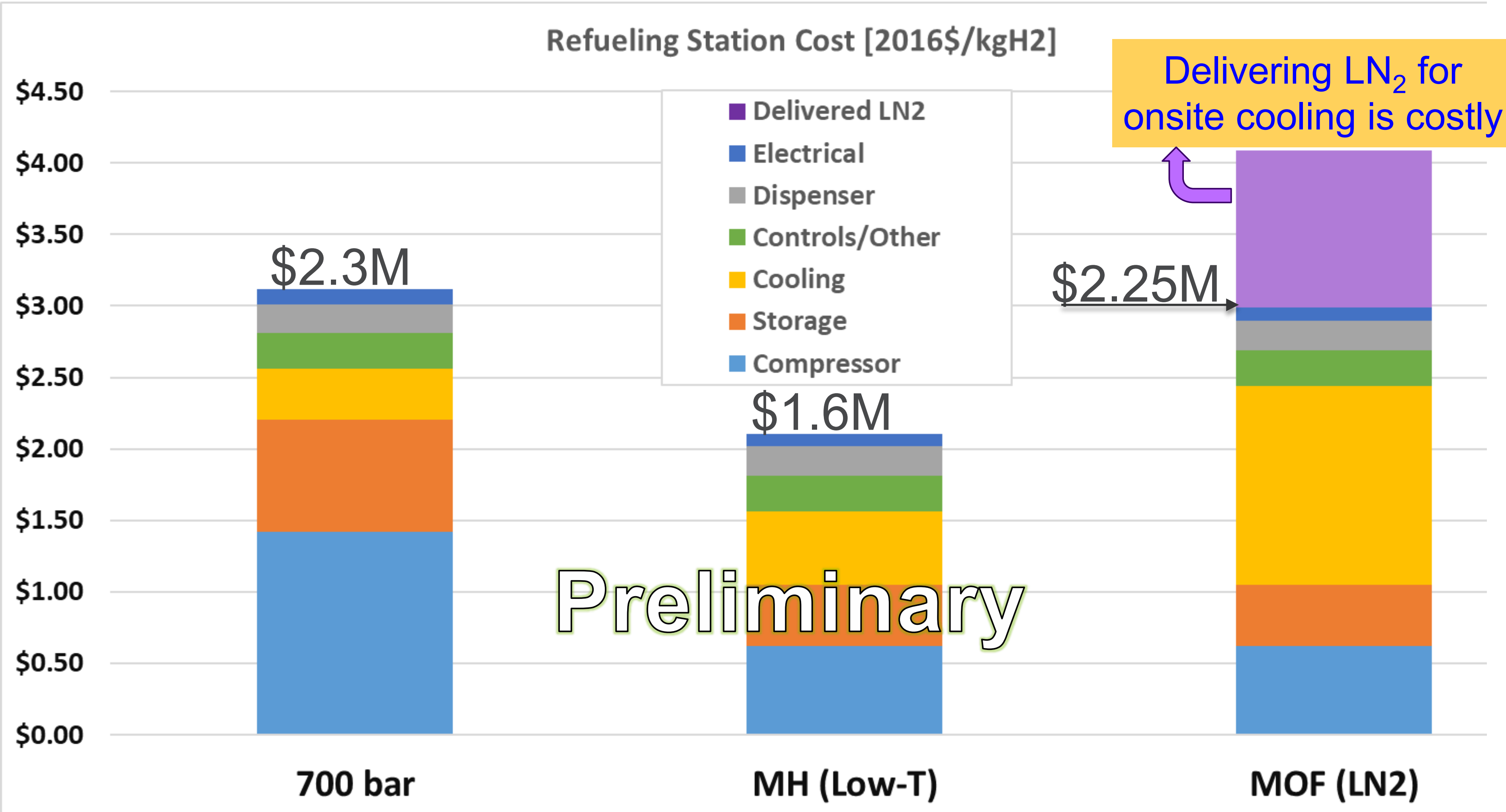
Scenario	Heat Duty	H_2 T_{inlet}	H_2 T_{outlet}	HX UA	HX Cost (per dispenser)
	kW	K	K	W/K	$
Cooler 1	94	300	151	1900	170,000
Cooler 2	4	151	145	45	7,000

Preliminary

- 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
- Preliminary LN_2 storage cost based on LH_2 storage cost
- LN_2 tank (6000 gallons) cost (uninstalled) = $185,000 ($140,000 future high volume)
- LN_2 pump capacity = 30 kg/min
- Pump cost (uninstalled) = $70,000 (per dispenser, high volume)
- HX cost is today low volume (uninstalled), high volume @55%, installation factor = 2

Based on assumptions of future MOF system that meets DOE H_2 storage targets

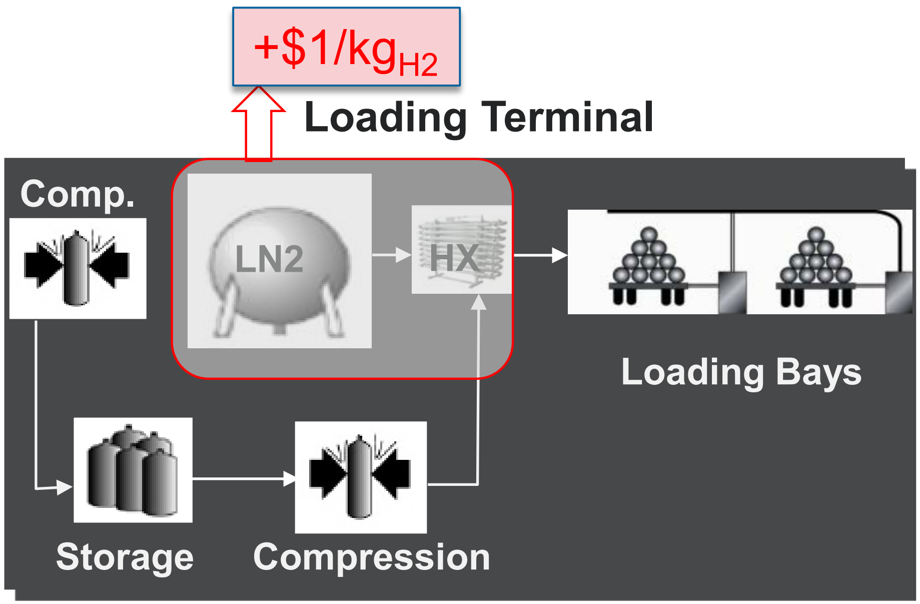
Evaluated Refueling Cost of Metal Hydride and MOF vs. 700 bar onboard Storage – Accomplishment



1000 kg/day station Capacity, 0.8 Capacity factor, 20bar H_2 supply, 4 dispensers

Evaluated Cost of Tube-Trailer Terminal for Cold gas Pathway – Accomplishment

- 8 kg_{LN2} is required to cool 1 kg_{H2} gas from 300K to 80K
- For $0.07 cost of 1 kg_{LN2} (range $0.07-$0.16/ kg_{LN2})
  → +$0.55 to cool 1 kg_{H2} gas from 300K to 80K
- $10M capital for 2M gallons LN_2 dewar (5-day supply)
  → +$0.15 per kg_{H2}
- $20M capital for LN_2 → H_2 heat exchanger/circulating pump
  → +$0.3 per kg_{H2}

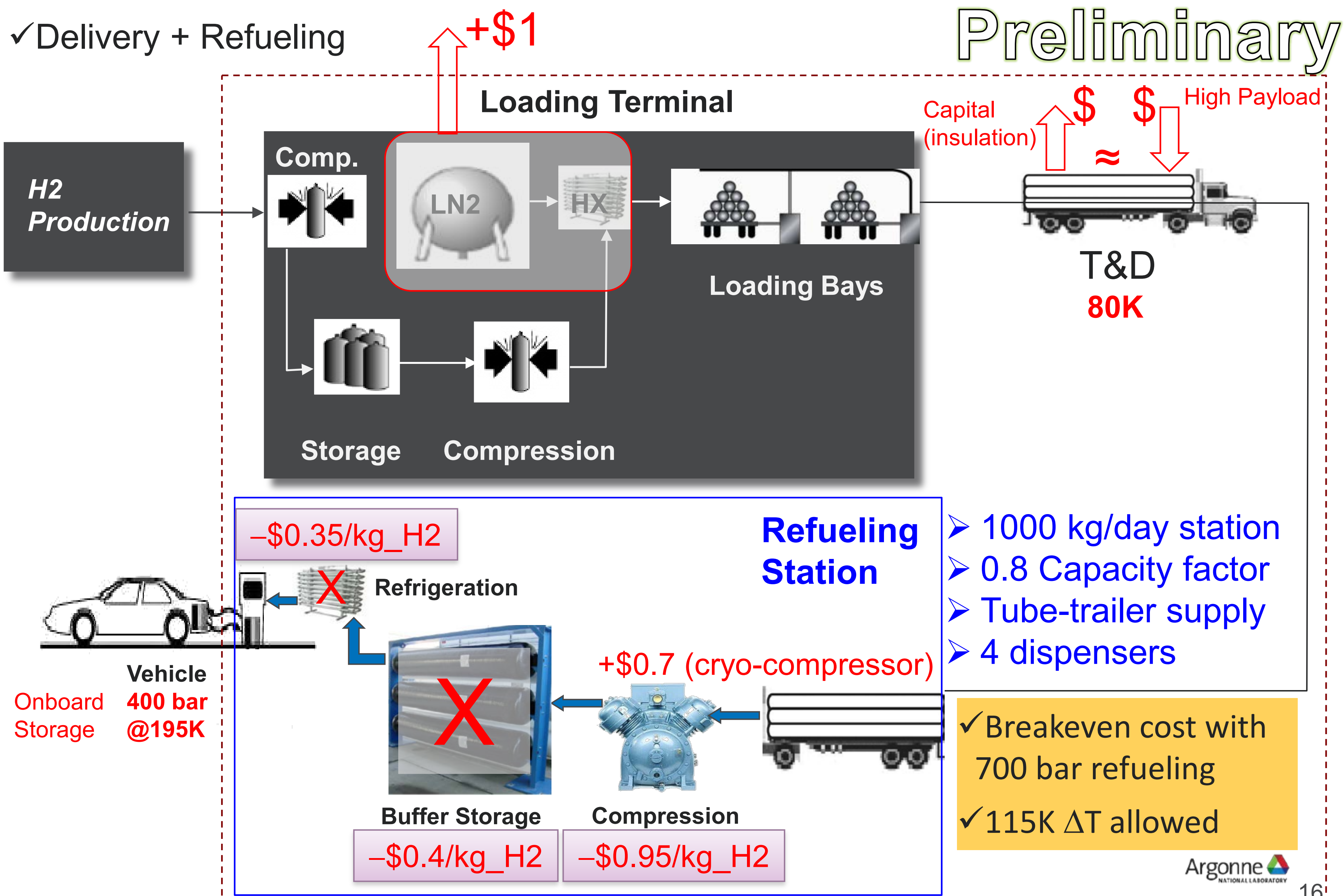


Preliminary

ΔTerminal Cost = +$1/$kg_{H2}$

Estimated Cost Of Cold H_2 Gas Pathway Relative to 700 bar Refueling with Tube-Trailer Supply – Accomplishment

✓Delivery + Refueling



- 1000 kg/day station
- 0.8 Capacity factor
- Tube-trailer supply
- 4 dispensers

✓Breakeven cost with 700 bar refueling

✓115K ΔT allowed

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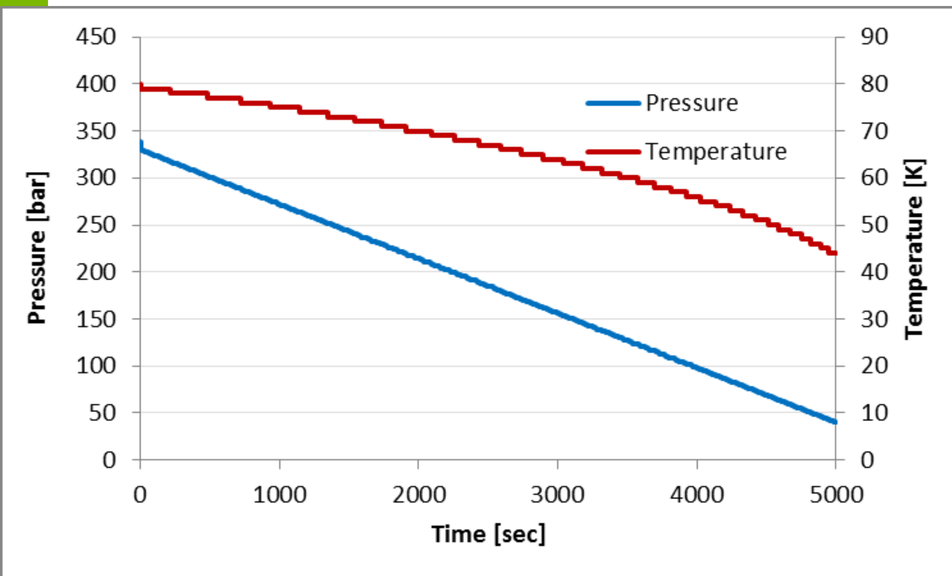
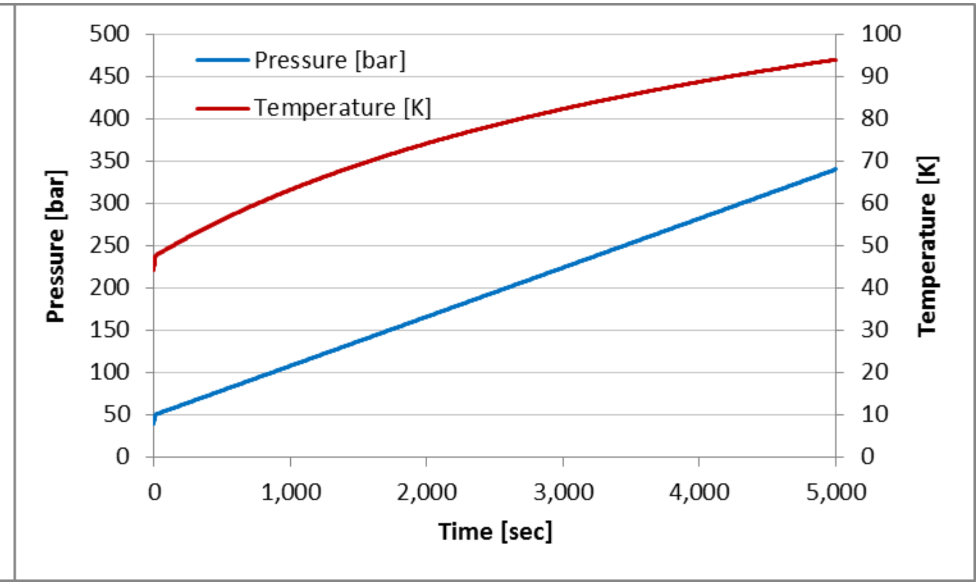
Evaluated Impact of Cold H_2 Gas Loading and Unloading on H_2 Temperature – Accomplishment

➢ Non-ideal expansion and compression (entropy generation)



Unloading Tube Trailer



Loading Tube Trailer

Simulations show +13°C with each unloading/loading cycle

✓ Assuming no external heat gain

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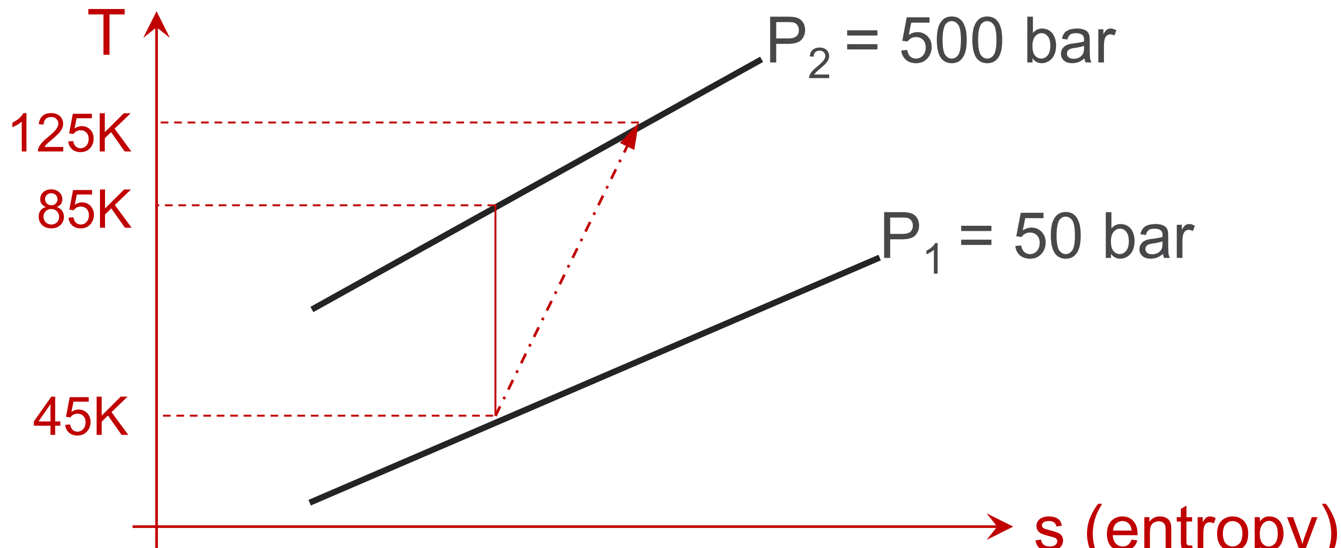
Cold H_2 Gas Pathway – Accomplishment

- ➢ Impact of heat of compression on temperature rise is significant

  - ➢ ΔT=+80°C drawing from an empty tube trailer (50 bar, 45K → 500 bar) →125 K discharge temperature (assuming cold compressor)

✓Assuming 60% isentropic efficiency, one stage compression



<u>Other considerations</u>:

- ➢ Impact of warm compressor and lines (thermal mass)
  - ✓ e.g., warm equipment after long idle time
- ➢ Impact of warm vehicle tank (>45K at start of refueling)

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Summary – Accomplishment

- Evaluated impact of onboard hydrogen storage options on refueling cost
  - Metal Hydride (MH) → 100 bar, near ambient temperature
  - Metal Organic Framework (MOF) → 100 bar, 145K
  - Cold Hydrogen Gas → 400 bar, 195K
  - ✓ Compare to 700 bar refueling
- MH provides the largest potential for refueling cost reduction
  - Cost reduction ~ $\$1/kg_{H2}$
  - Most of the cost reduction is attributed to low refueling pressure
  - Hose size is a concern→ station attendant may be needed
- MOF 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 $\$1/kg_{H2}$
- Cold gas provides limited refueling cost reduction potential
  - Breakeven with 700 bar refueling cost
  - Impact of entropy increase due to isenthalpic expansion, compression and components' thermal mass must be carefully considered
- MH, MOF and cold gas onboard storage systems require varied refueling pressure and temperature, thus impacting refueling cost differently

Collaborations and Acknowledgments

- Guillaume Petitpas, Lawrence Livermore National Laboratory supported the calculations of cold gas pathway
- Daryl Brown of Energy Technology Analysis supported the MOF pathway analysis
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- Jesse Adams (DOE) provided technical information and general guidance and support
- David Tamburello of Savannah River National Laboratory provided performance data for MOF systems
- Kriston Brooks and Ewa Ronnebro of Pacific Northwest National Laboratory provided performance data for MOF systems
- Terry Johnson of Sandia National Laboratory provided performance data for MH systems
- U.S.DRIVE Delivery and Storage Tech Teams

Future Work

Any proposed future work is subject to change based on funding levels

- Confirm design, performance and cost of refueling equipment via vendor quotes
  - Heat exchangers
  - LN_2 storage and pump
  - Low-pressure compressor
  - Terminal cost and cryo-compressor for cold H_2 gas pathway
- Verify impact of on temperature increase for cold H_2 gas pathway
- Expand system boundary to include delivery + refueling cost for consistent comparison
- Consider LH_2 for 77K MOF refueling
- Consider ambient temperature MOF refuleing
- Include cryo-compressed H_2 pathway in the comparative analysis
- Implement new pathways in HDSAM
  - Conduct independent model review by experts
  - Release updated HDSAM
- Conduct sensitivity analysis on the key cost parameters
- Document data and analysis in peer-reviewed publication

Project Summary

- **Relevance**: On-board hydrogen storage systems can have large impact on delivery and refueling cost
- **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 MH, MOF and cold H_2 gas on refueling cost
  - MH provides the largest potential for refueling cost reduction compared to 700 bar refueling (~$1/$kg_{H2}$)
  - MOF shows increase in cost of refueling mainly due to LN_2 onsite cooling
  - Cold gas refueling cost breakeven with 700 bar refueling
    - Impact of entropy increase due to isenthalpic expansion, heat of compression, and components' thermal mass must be carefully considered
- **Future Research**:
  - Confirm design, performance and cost of refueling equipment via vendor quotes
  - Expand system boundary to include delivery + refueling cost for consistent comparison
  - Implement new pathways in HDSAM
  - Conduct sensitivity analysis on the key cost parameters

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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
- LLNL: Lawrence Livermore National Laboratory
- 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
- 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