FEBRUARY 27, 2024

HFTO HYDROGEN INFRASTRUCTURE WORKSHOP

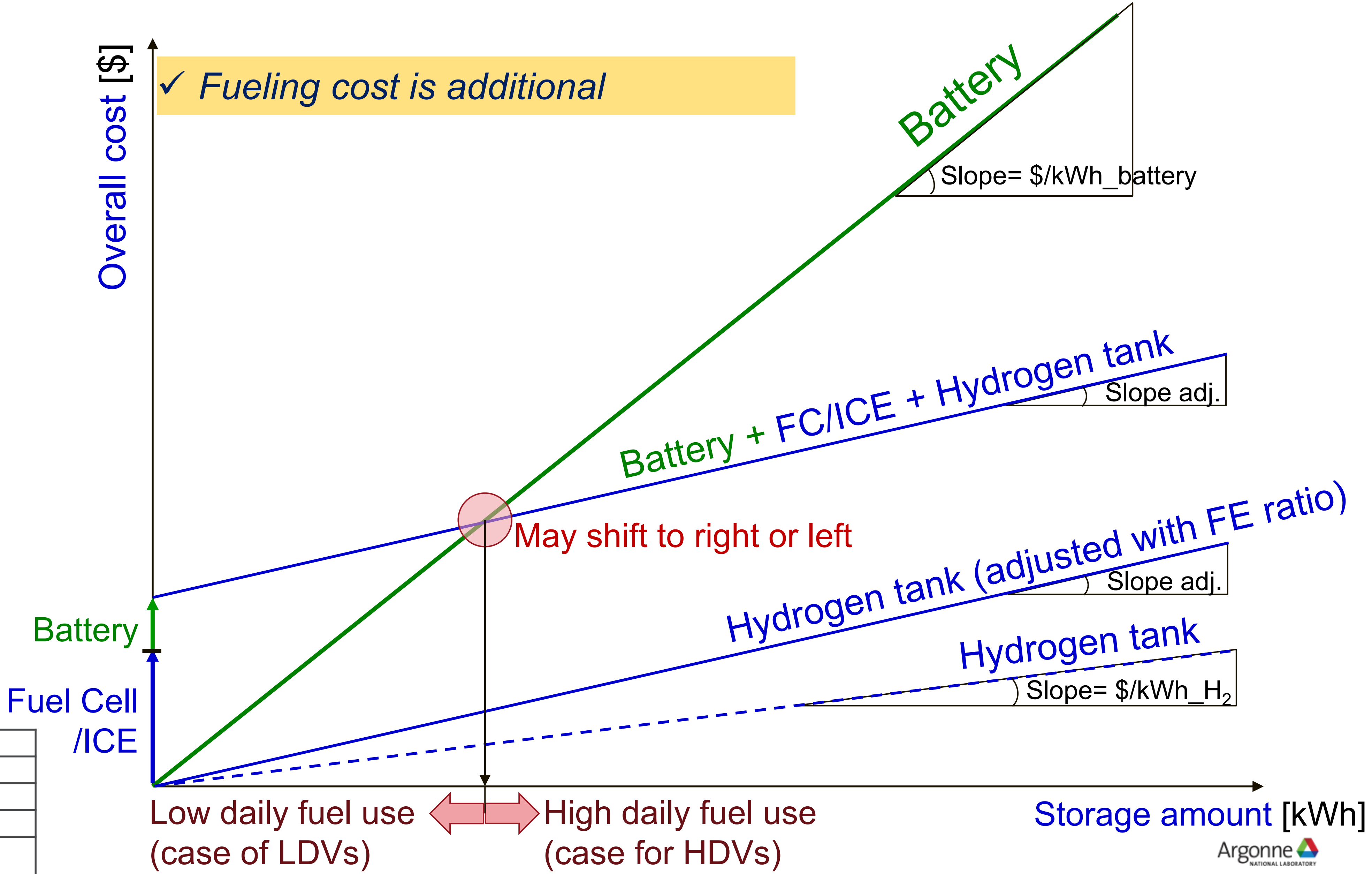
Hydrogen fueling cost analysis of various onboard storage technologies

Amgad Elgowainy, PhD

Senior Scientist, Distinguished Fellow, and Group Leader

Systems Assessment Center
Energy Systems and Infrastructure Analysis Division
Argonne National Laboratory

H_2 fuel cell electric vehicles are attractive zero-emission options when daily energy use is high *(vehicle cost perspective)*



✓FC: Fuel Cell
✓ICE: Internal Comb. Engine
✓FE: Fuel Economy
✓LDV: Light-Duty Vehicle
✓HDV: Medium- and Heavy-Duty Vehicle

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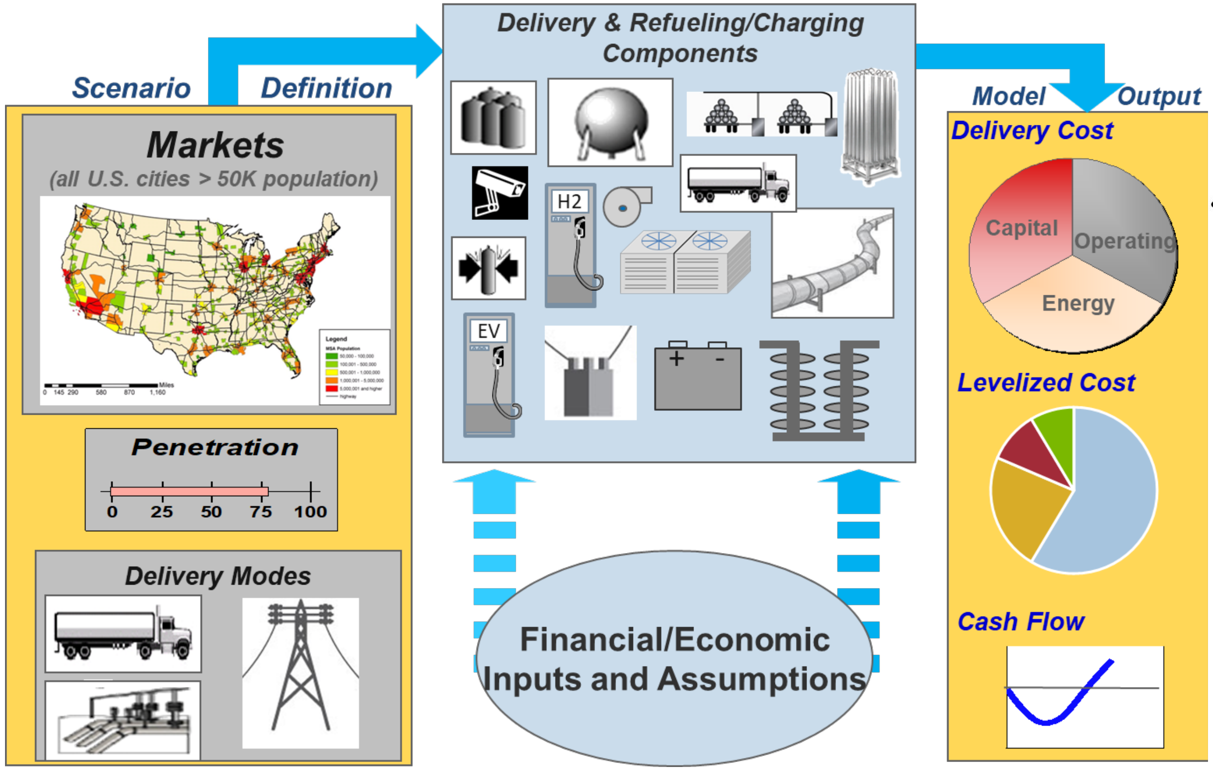
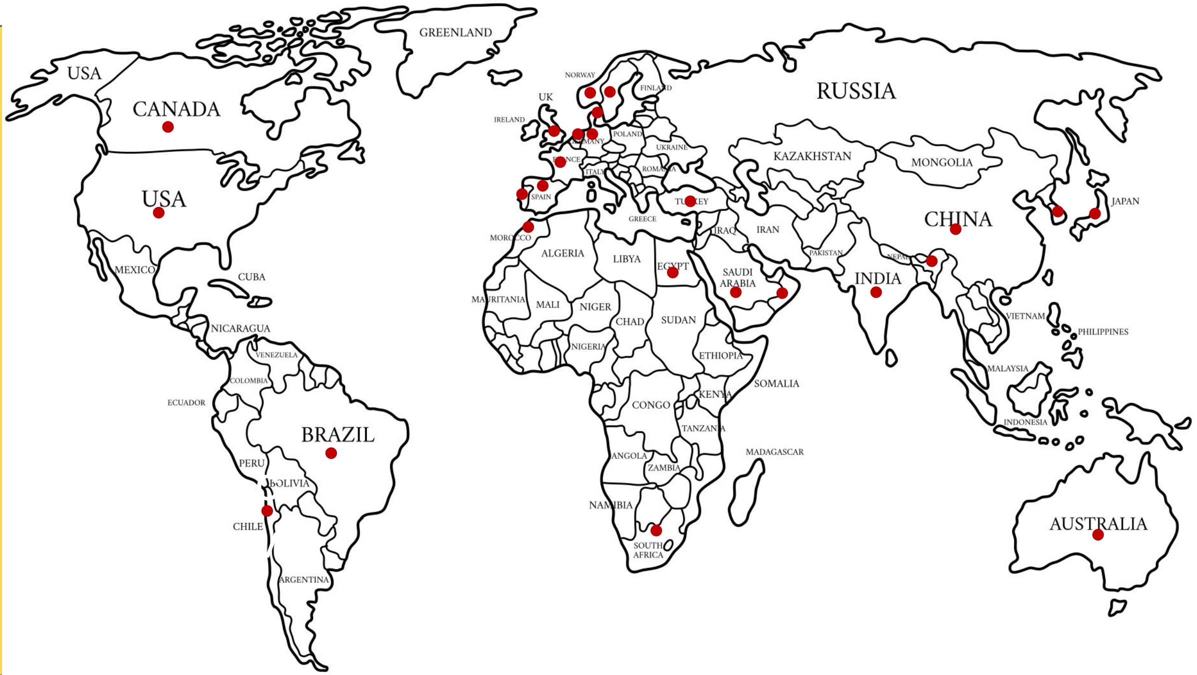
Hydrogen Delivery Scenario Analysis suite of Models (HDSAM)

Argonne's HDSAM and its derivatives evaluate the economic performance and market acceptance of hydrogen delivery technologies and fueling infrastructure for FCEVs

- Publicly available with >5,000 users, including major gas and energy companies, in more than 25 countries
- Supported by U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office (HFTO) since 2004

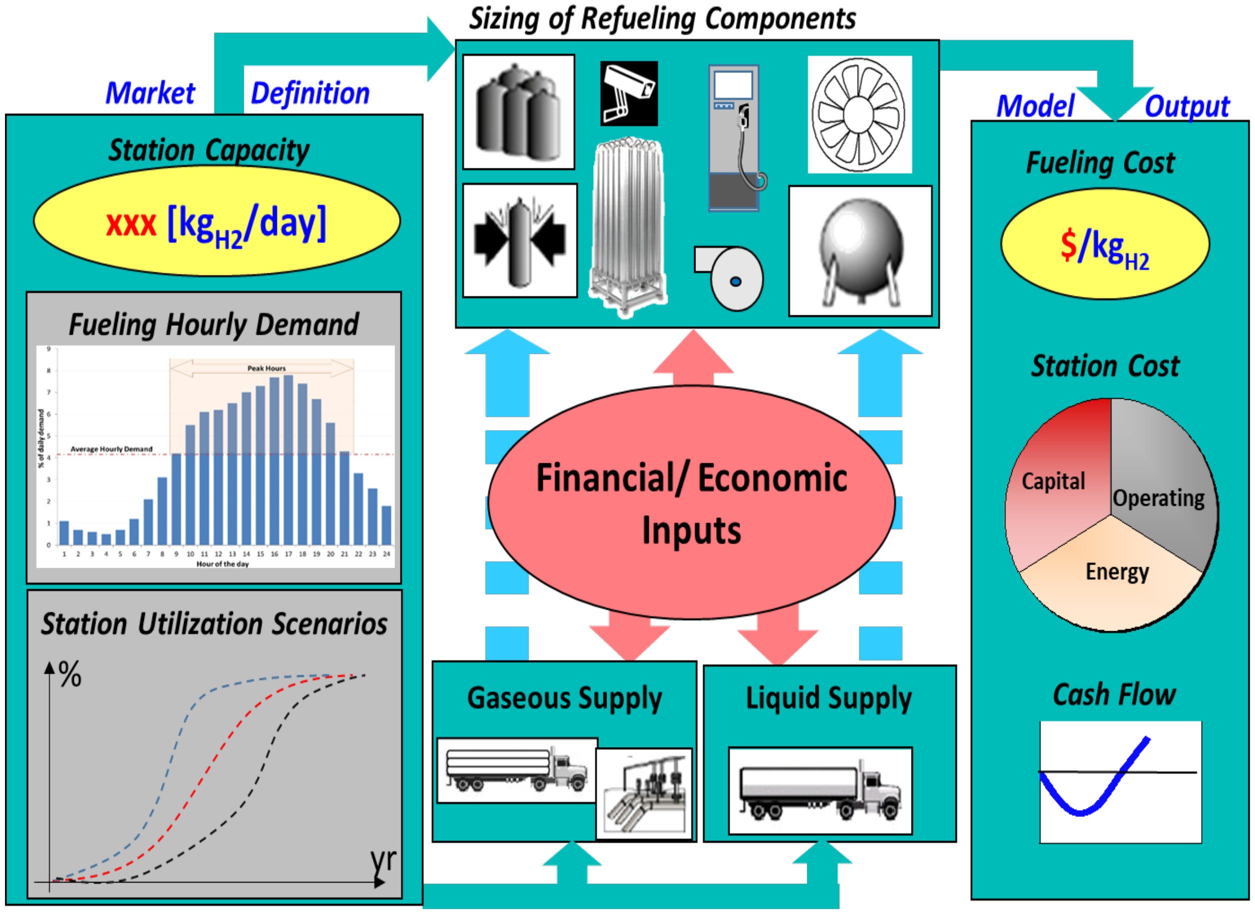




Fueling model for fuel cell HDVs is different from LDVs

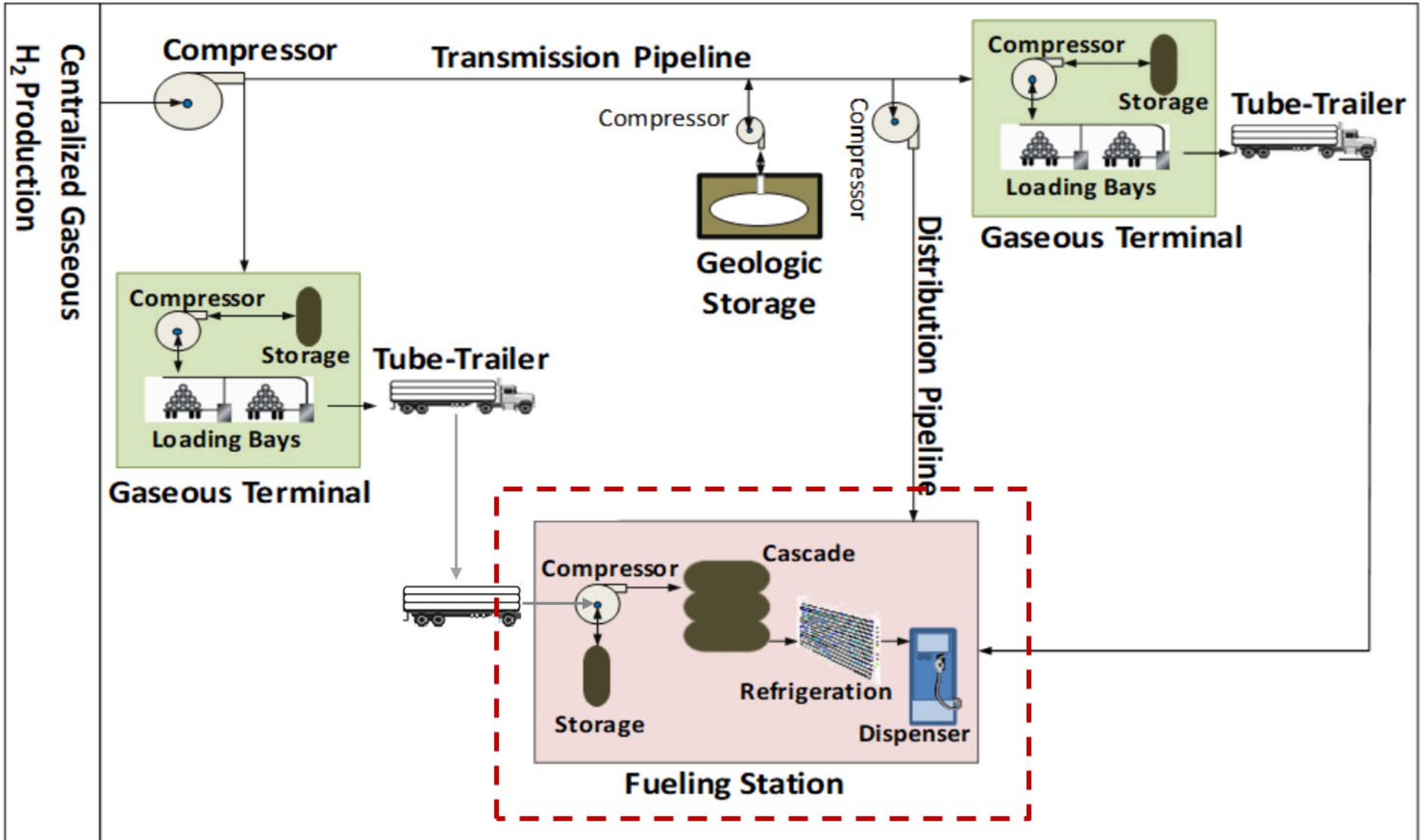
- Hydrogen fueling cost for HDVs is different from LDV
  - fill amount
  - fill rate
  - fill strategy
  - fueling pressure
  - precooling requirement, etc.

Requires different design strategies with respect to buffering compressor and refrigeration systems



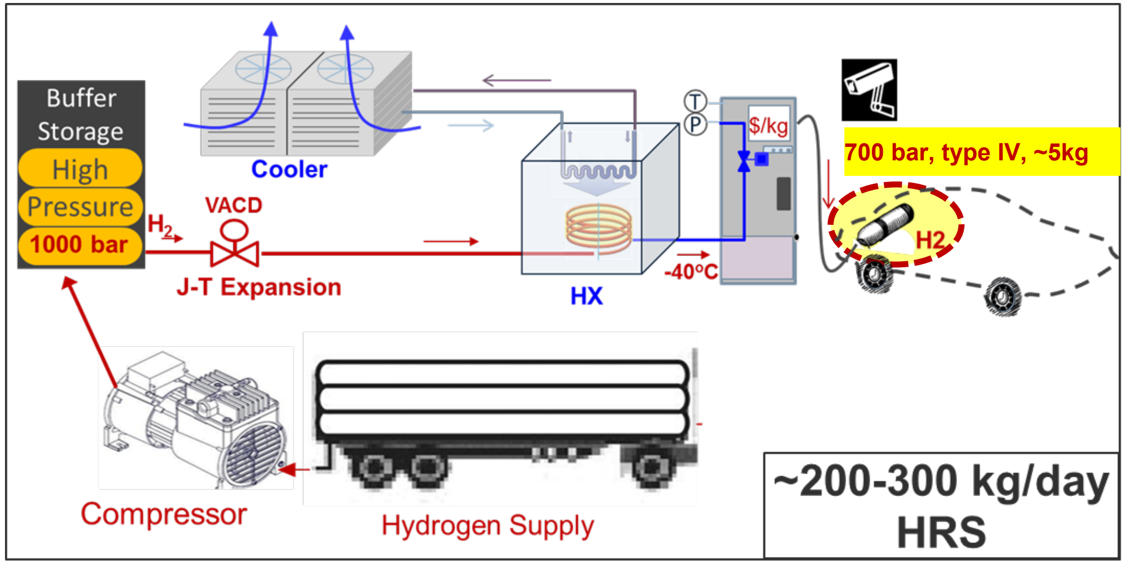
https://hdsam.es.anl.gov/index.php?content=hdrsam

Gaseous hydrogen delivery to HRS requires complex logistics of H_2 supply and station design

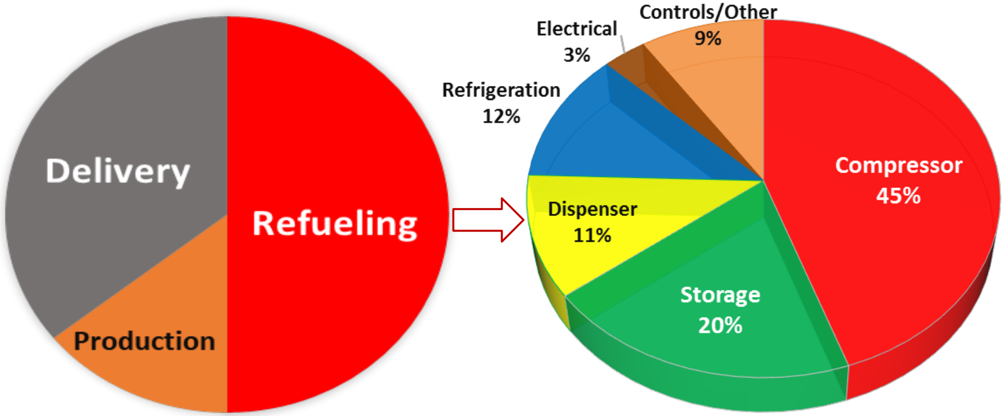


HRS = H_2 Refueling Station

Cost of hydrogen delivery and refueling for FCEVs is strongly driven by onboard storage requirement and H_2 supply chain



✓ HX: Heat Exchange	✓ VACD: Variable Area Control Device
✓ J-T: Joule-Thomson	✓ CA: California



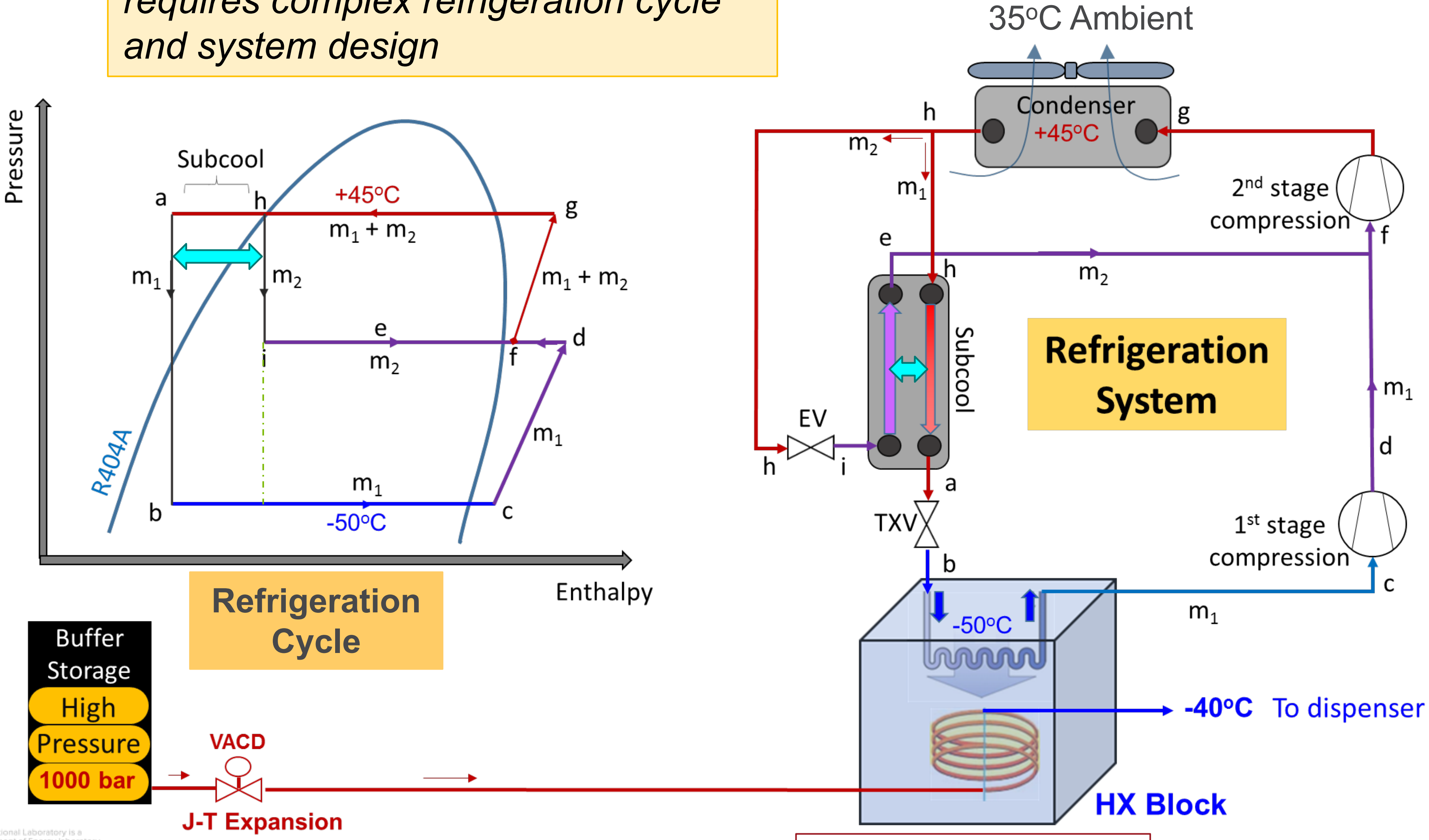
Bulk of H_2 cost is in delivery and refueling

HRS

https://www.sciencedirect.com/science/article/pii/S0360319917320311

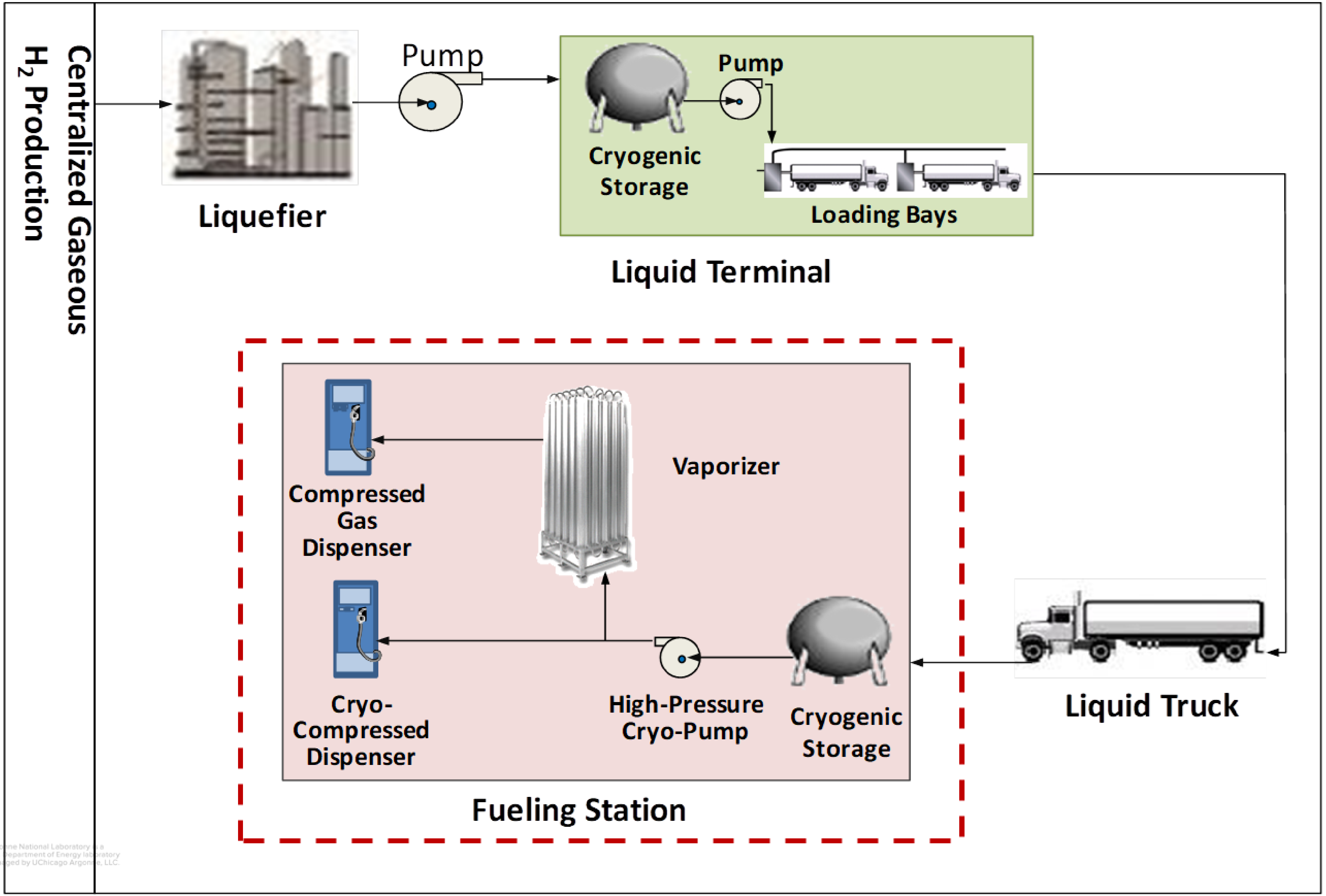
Typical refrigeration system used in HRS requires ~ 15-20kW precooling capacity per each 1 kg/min dispensing

Low temperature (-40°C) precooling requires complex refrigeration cycle and system design

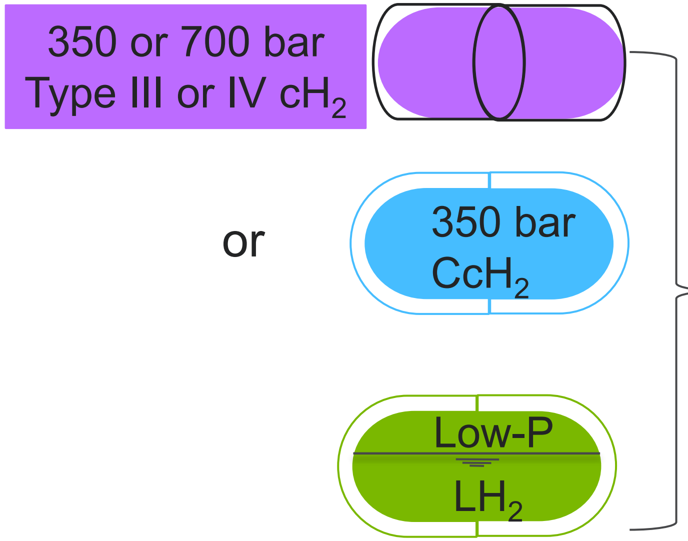


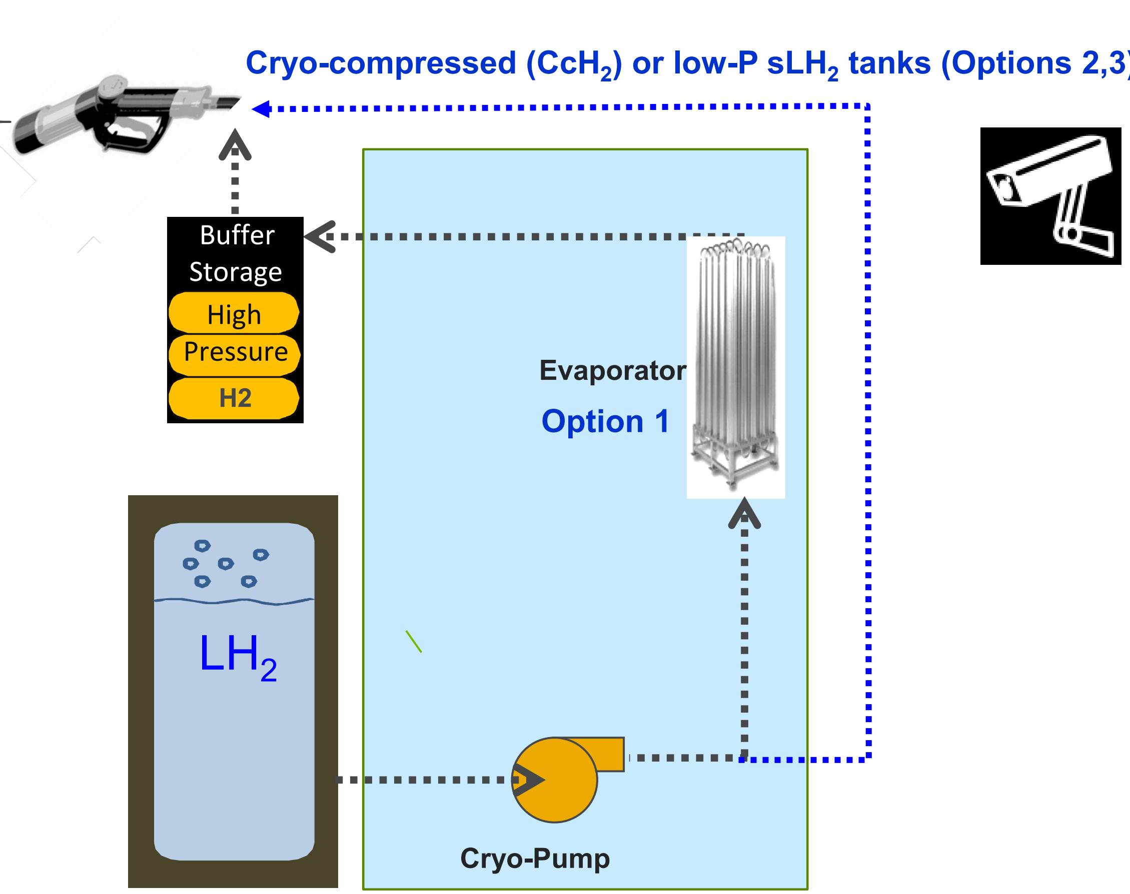
HX capacity = UA $\Delta T_{log\text{-}mean}$

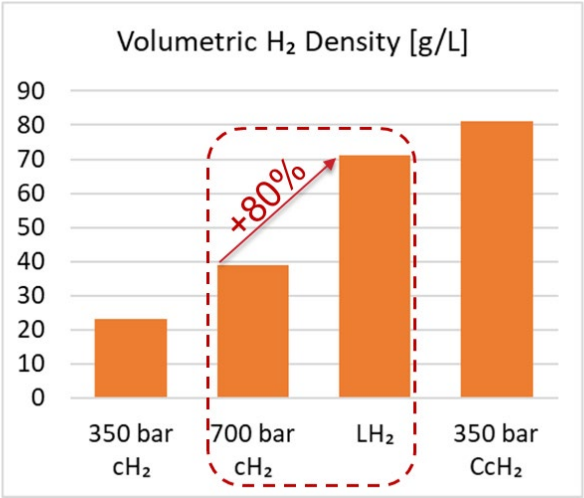
Liquid hydrogen (LH_2) delivery simplifies station design



Versatile refueling configurations with LH_2 delivery: simplifies HRS configuration



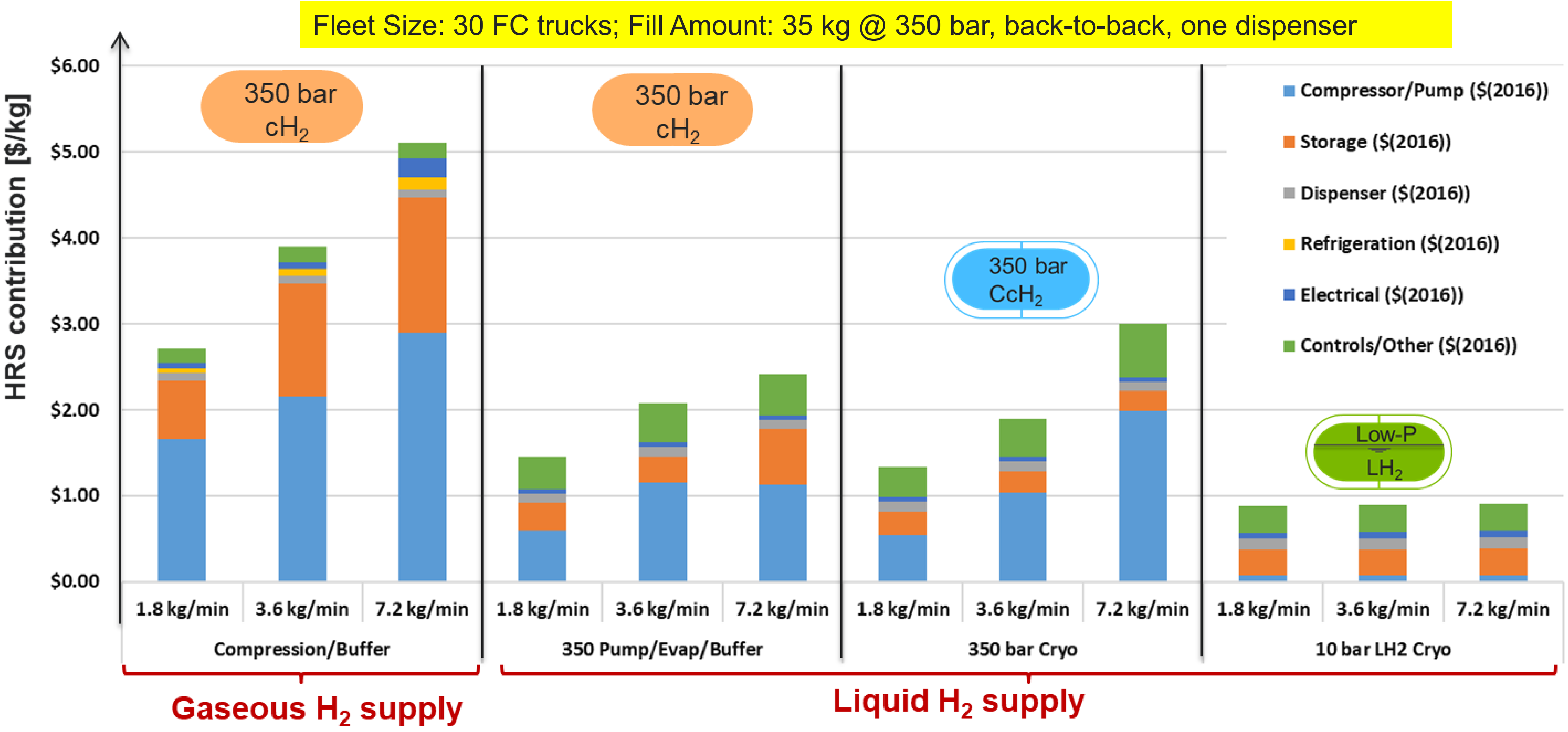




- ✓ LH_2: Liquid Hydrogen
- ✓ CcH_2: Cryo-compressed hydrogen
- ✓ cH_2: compressed hydrogen
- ✓ Low-P: Low Pressure (<10 bar)

Refrigeration unit can be avoided with proper thermal energy recovery

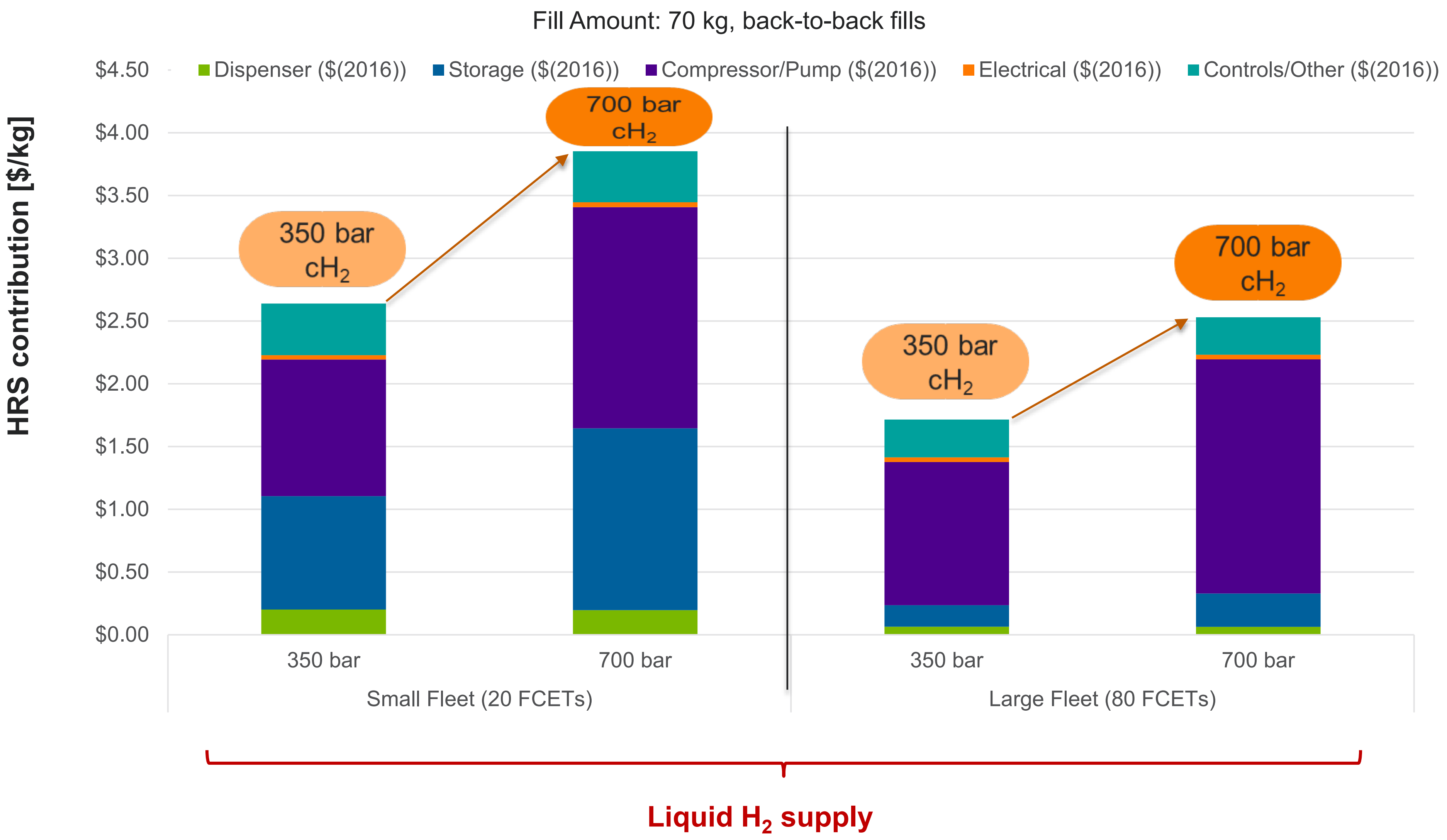
Liquid H_2 supplied stations can handle faster fills with lower cost compared to gaseous H_2 supply



➢ Compression and pumping are key cost drivers

700 bar tanks dramatically increase HRS cost, even with LH_2 supply

Class 8, long-haul trucks



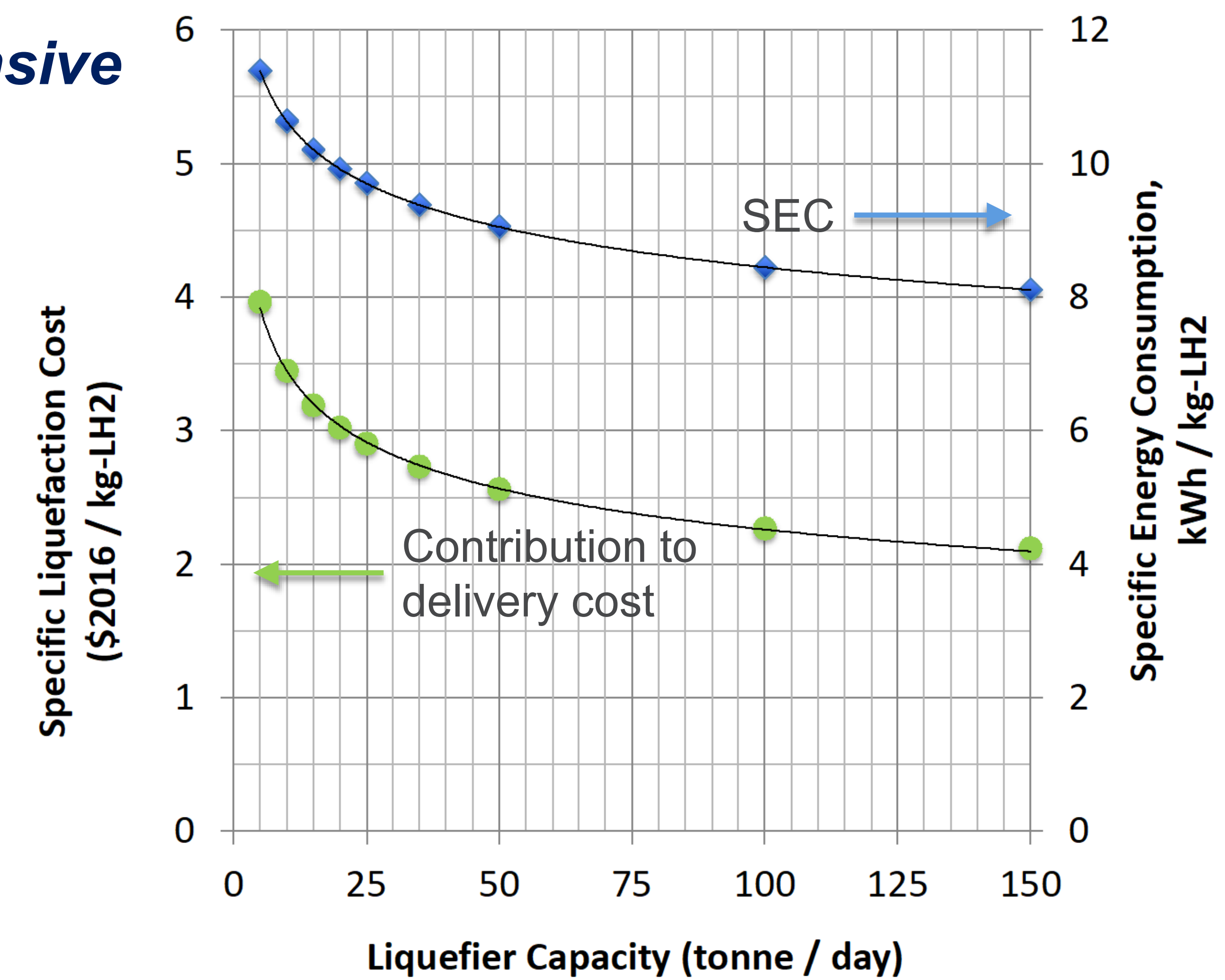
➢ MDVs and buses can benefit from 350 bar fueling due to lower daily VMT and available space for CHSS

H_2 liquefaction is energy and cost intensive

- Scaling laws based on aggregation of industry input
  - Liquefier CAPEX
  - Specific energy consumption (SEC)

- Modeling and analysis in the literature suggest SEC can potentially be as low as 6 kWh/kg

- SLC – Specific liquefaction cost



Delivered	Liquefier	SLC	SEC	GHG Emissions 2021 (US mix)
	5 tpd	$4.0 / kg-LH2	11 kWh / kg	4.8 $kgCO_{2e}$ / kgH_2
30 tpd	33 tpd	**$2.8 / kg-LH2**	**9.4 kWh / kg**	**4.1 $kgCO_{2e}$ / kgH_2**
120 tpd	130 tpd	**$2.1 / kg-LH2**	**8.2 kWh / kg**	**3.6 $kgCO_{2e}$ / kgH_2**

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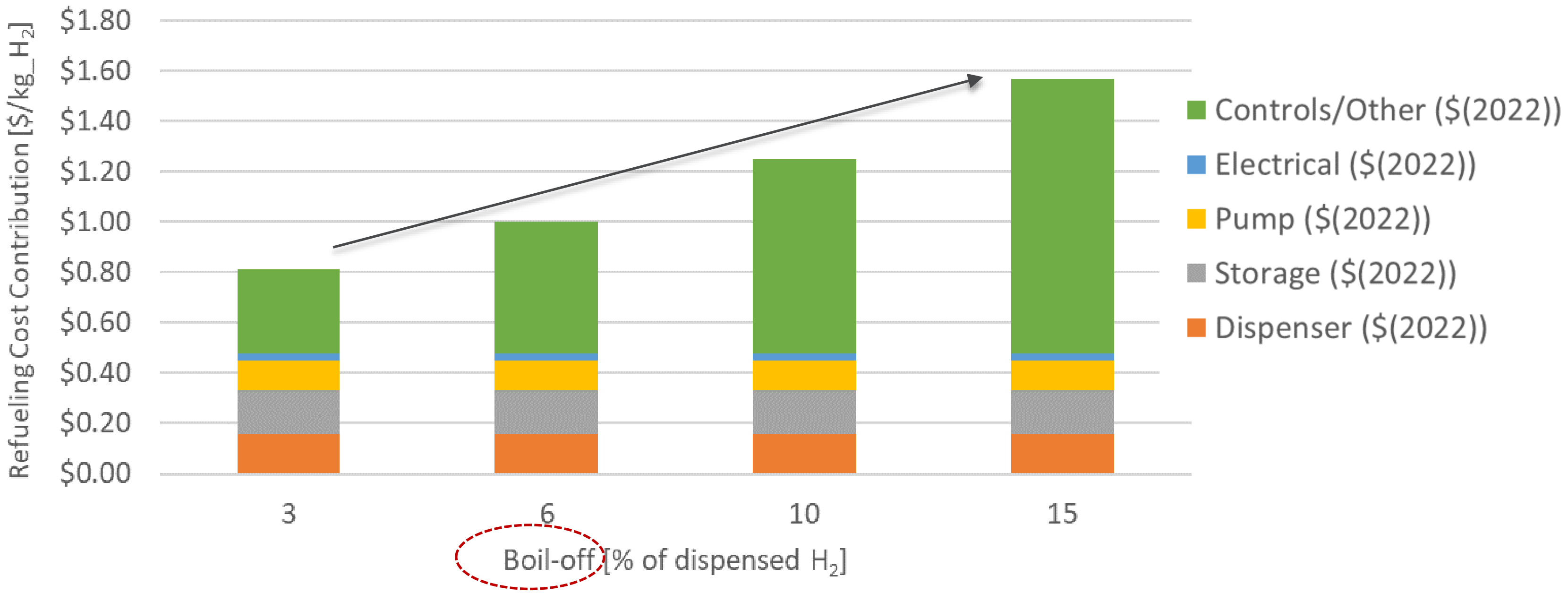
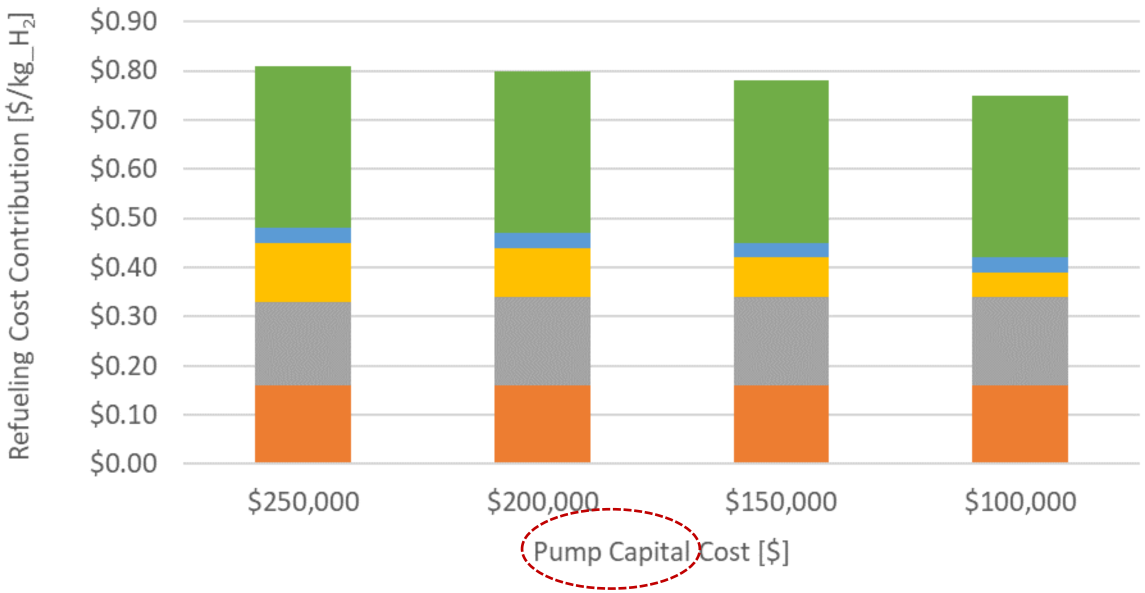
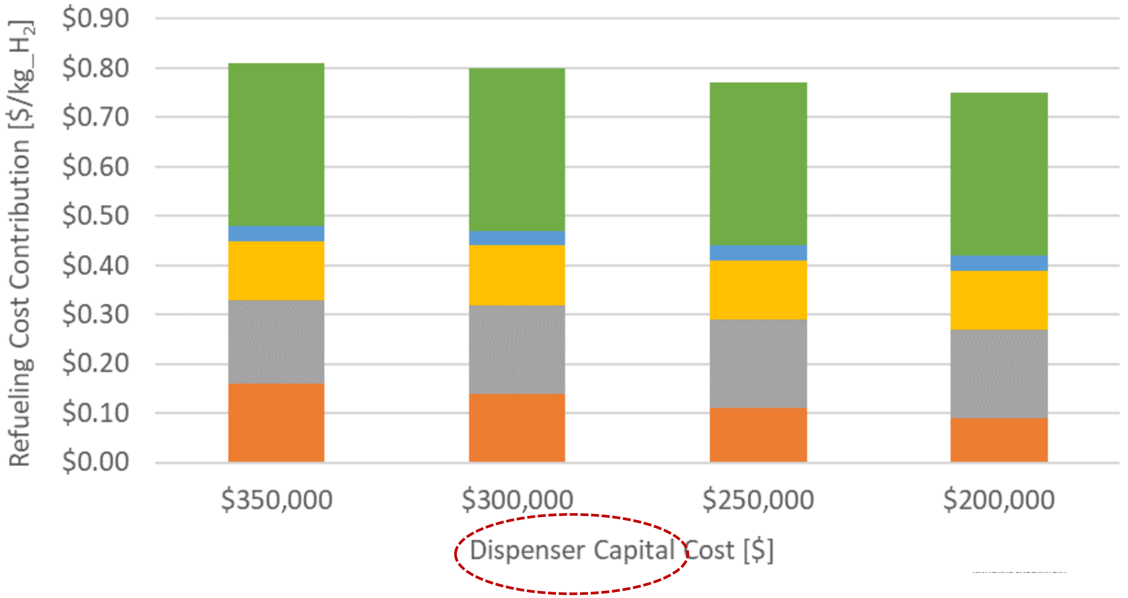
Cost associated with boiloff losses can be significant (depends on LH_2 cost)

Example: sLH_2 HRS

$6/kg Delivered LH_2 cost is assumed for boiloff impact







Conclusions

- Cost of hydrogen fueling depends strongly on H_2 delivery phase (i.e., gaseous vs. liquid) and vehicle's onboard storage design
- Cost and reliability of pump are key cost drivers
- CcH_2 and sLH_2 onboard storage can potentially reduce HRS cost contribution compared to 350 and 700 bar CH_2 onboard storage
  - ➢ but energy density for CcH_2 > sLH_2 > 700 bar CH_2 > 350 bar CH_2
- Boiloff losses associated with cryogenic delivery to onboard storage is most impactful but most uncertain parameter
  - ➢ Requires careful assessment for CcH_2 and sLH_2 onboard storage fueling
- Liquefaction energy and carbon intensity are important considerations

Acknowledgment

Hydrogen fueling cost at Argonne have been supported by DOE's Office of Energy Efficiency and Renewable Energy's Hydrogen and Fuel Cell Technologies Office (HFTO) for over two decades

Thank You!

aelgowainy@anl.gov

Our models, tutorials and publications are available at:

https://hdsam.es.anl.gov/