OPPORTUNITIES AND CHALLENGES OF LIQUID HYDROGEN SUPPLY CHAIN

Amgad Elgowainy, PhD
Senior Scientist and Group Leader

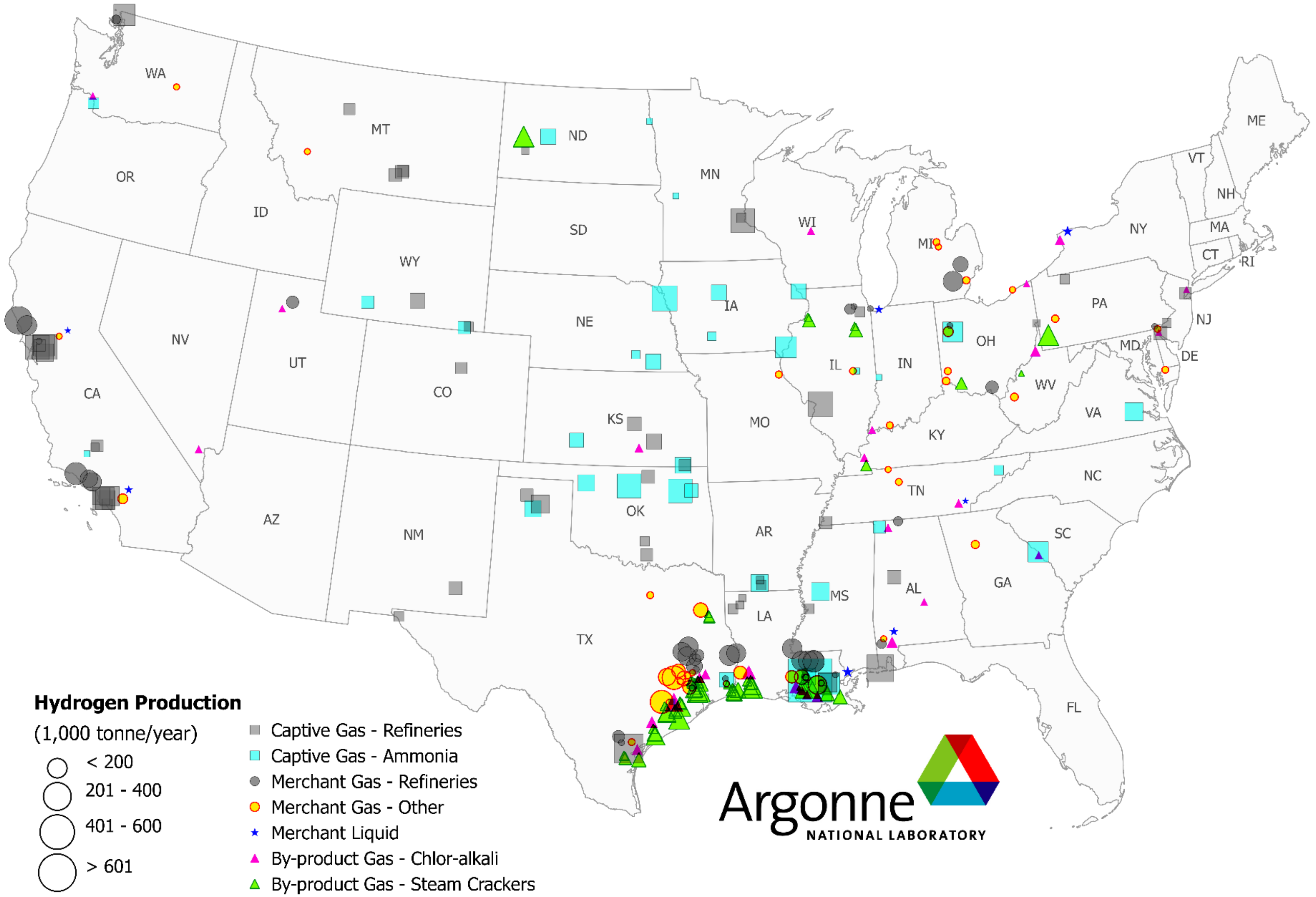
Ed Frank, PhD
Principal Energy Systems Scientist

Argonne National Laboratory

Presentation at Liquid Hydrogen Technologies Workshop
February 22, 2022

Today, more than 10M metric tons of hydrogen are produced in the U.S. annually near their end use

1600 mi. of H_2 pipeline; **10** Liquefaction plants in North America



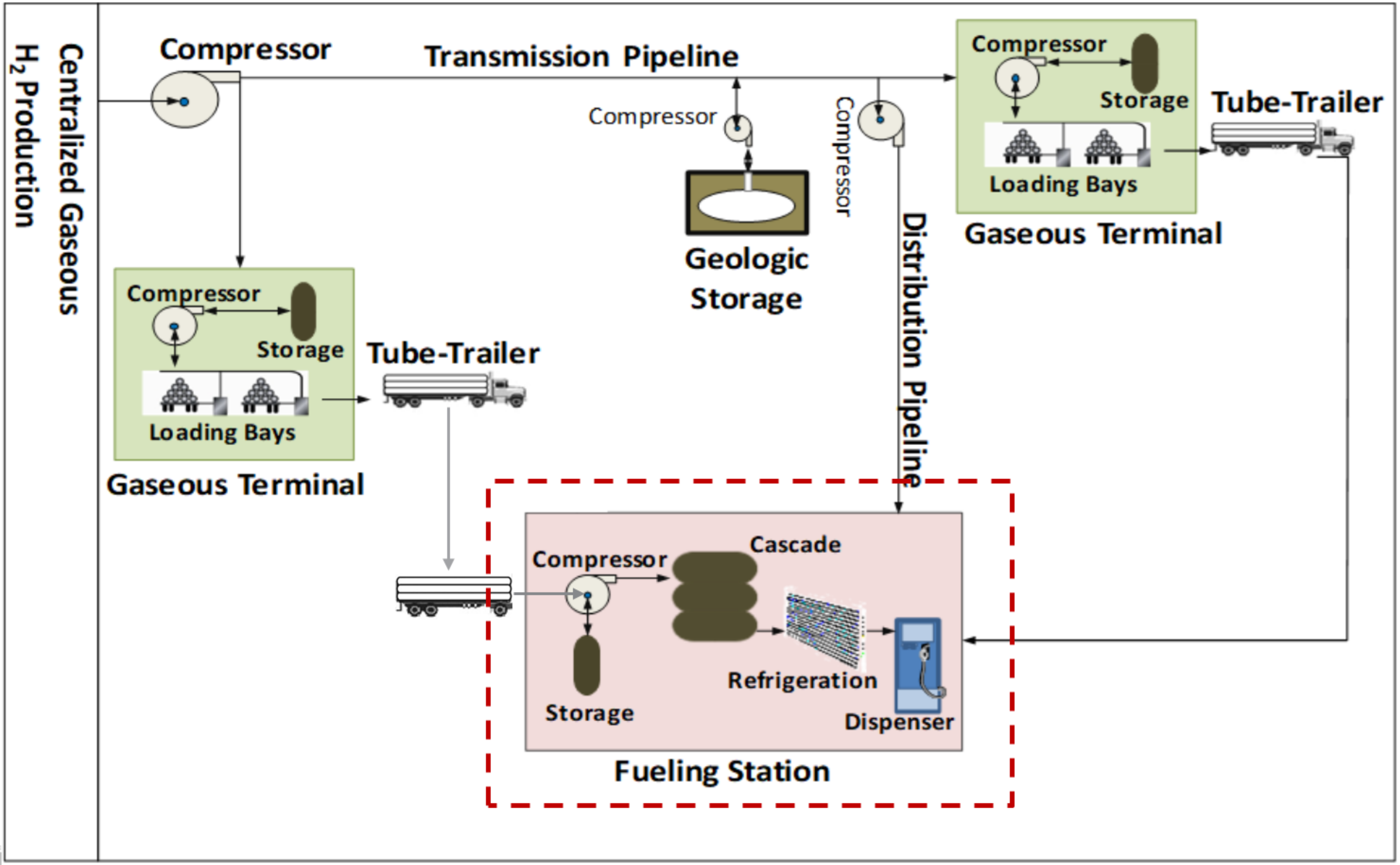
~260 MT/day H_2 liquefaction capacity in North America

Region	Liquefaction Capacity (MT/day)
California	30
Louisiana	70
Indiana	30
New York	40
Alabama	30
Ontario	30
Quebec	27
Tennessee	6
Total	263

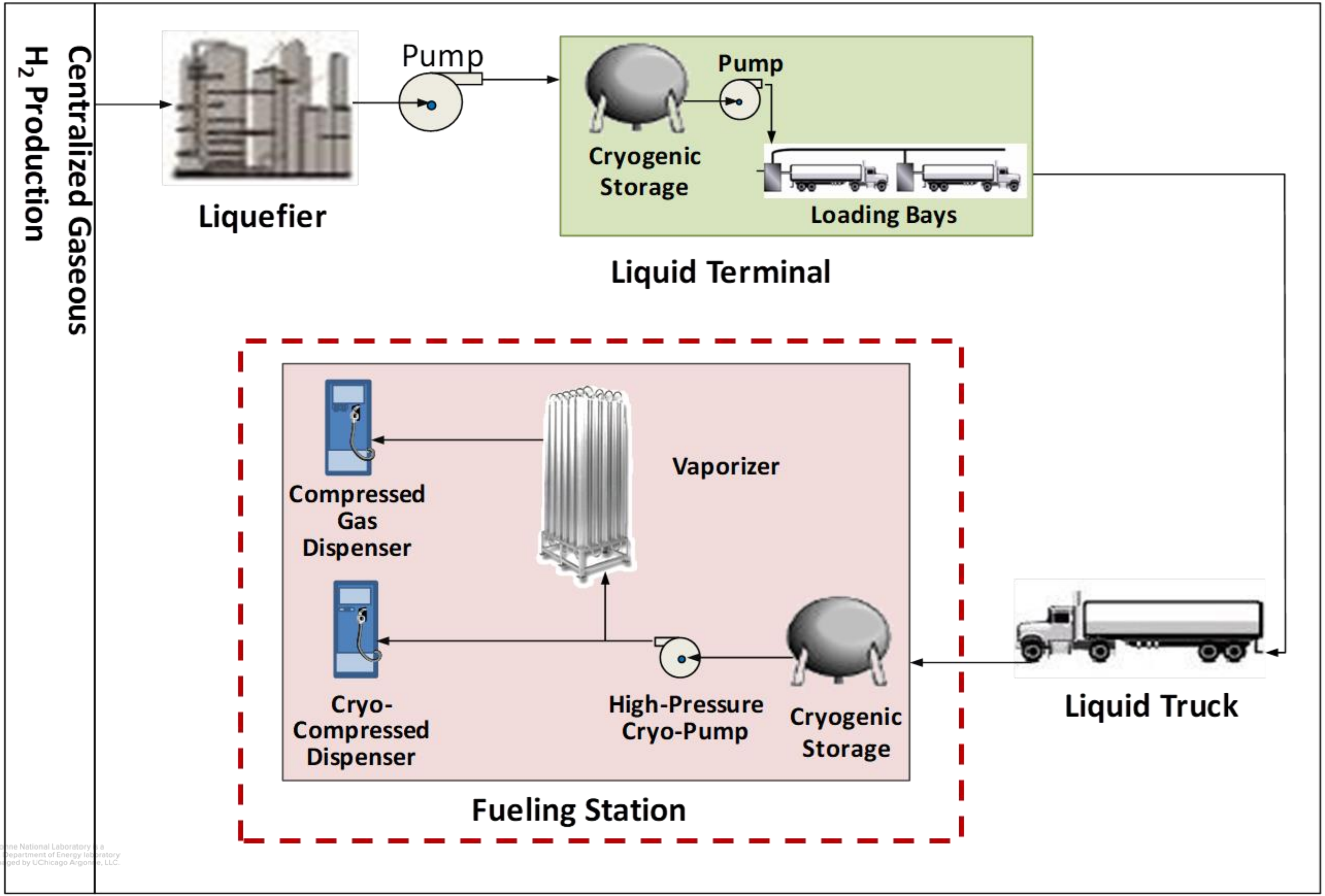
→ Liquefaction energy intensity = 10-15 $kWhe/kg_{H_2}$

Four additional H_2 liquefaction plants have been recently announced to serve the growing H_2 market

Infrastructure of gaseous hydrogen delivery



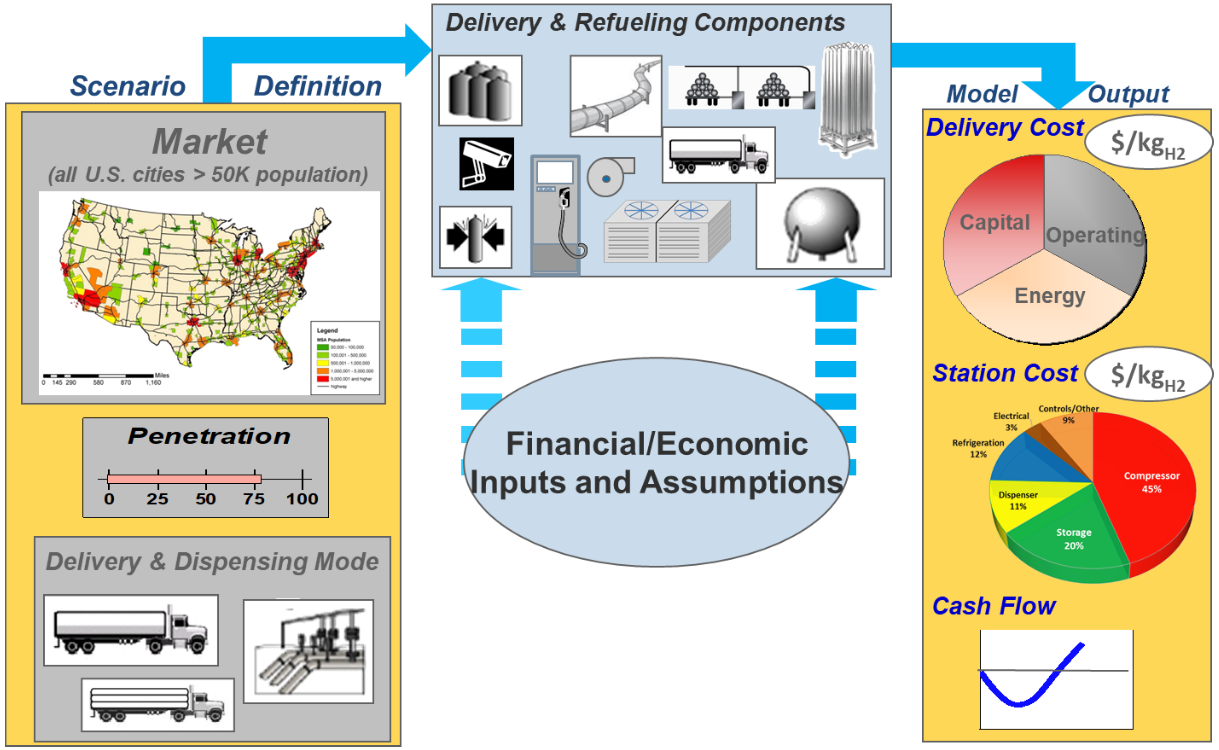
Infrastructure of liquid hydrogen delivery



Argonne models evaluate techno-economics and environmental implications of H_2 production and delivery

HDSAM

Techno-economic Evaluation



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

GREET

Environmental Life Cycle Evaluation

Energy use	Air pollutants	Greenhouse gases	Water consumption
• Total energy: fossil energy and renewable energy • Fossil energy: petroleum, natural gas, and coal • Renewable energy: biomass, nuclear energy, hydro-power, wind power, and solar energy	• VOC, CO, NOx, PM_{10}, $PM_{2.5}$, and SOx • Estimated separately for total and urban (a subset of the total) emissions	• CO_2, CH_4, N_2O, black carbon, and albedo • CO_{2e} of the five (with their global warming potentials)	• Addressing water supply and demand (energy-water nexus)

Life cycle modeling of fuel cell and baseline vehicle/fuel systems

https://greet.es.anl.gov/

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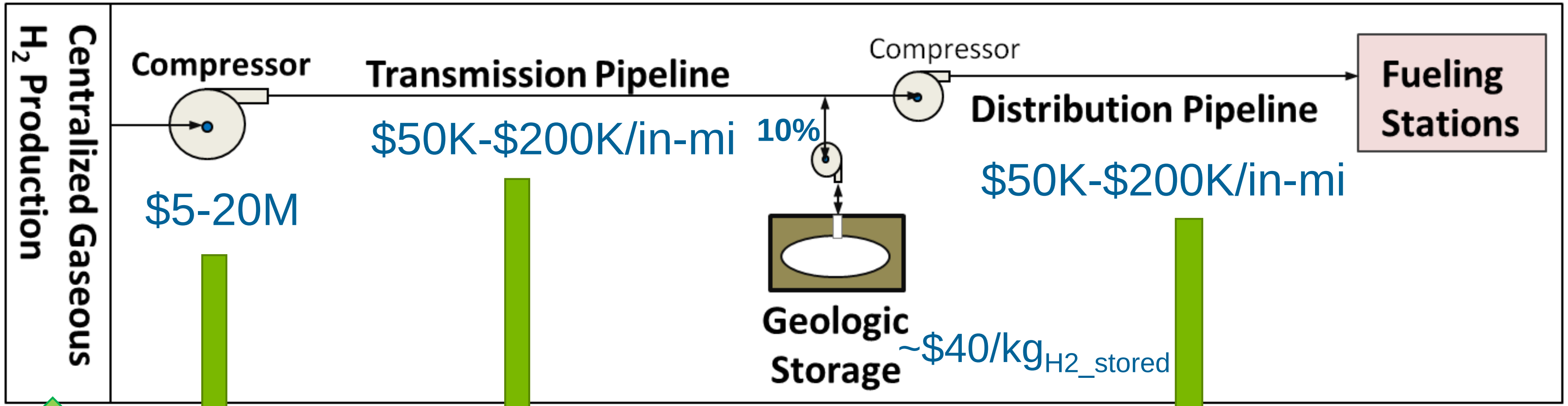
Cost contribution of pipeline delivery



50-1000 MT/day

~$0.1/kg$_{H2}$

~$0.1-$0.2/kg$_{H2}$

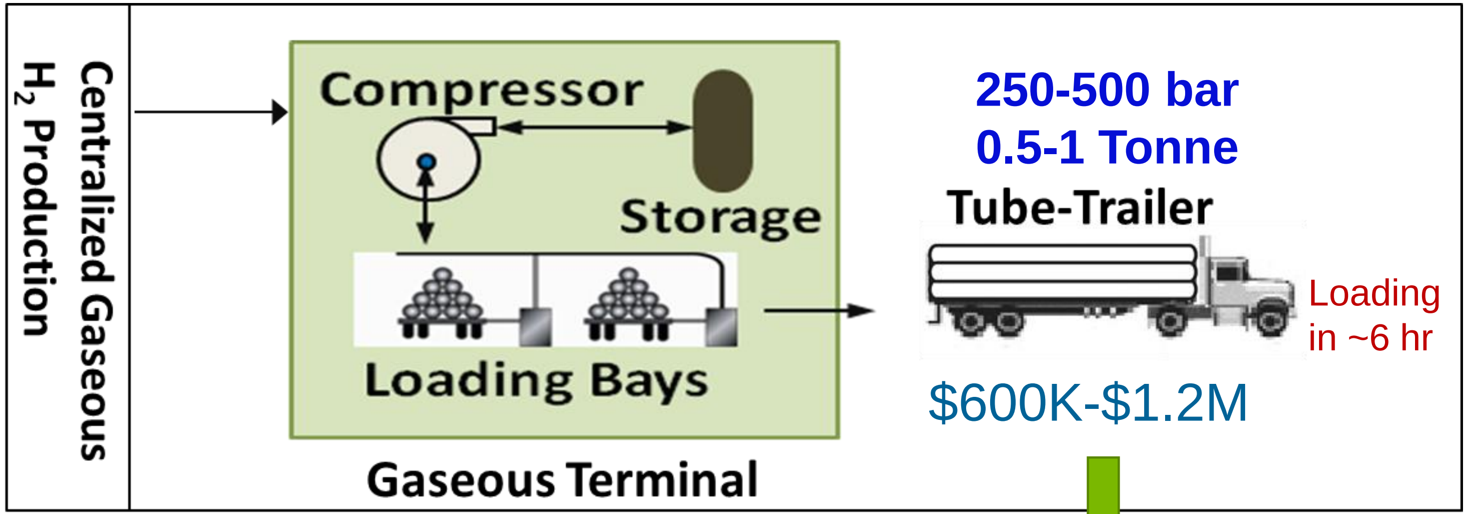
~$0.10-$0.5/kg$_{H2}$.100mi

~$0.2-$0.5 /kg$_{H2}$

Total delivery cost $0.5 : $1 / kg$_{H2}$

1000 MT/day   50 MT/day

Cost contribution of tube-trailer delivery



30-100 MT/day

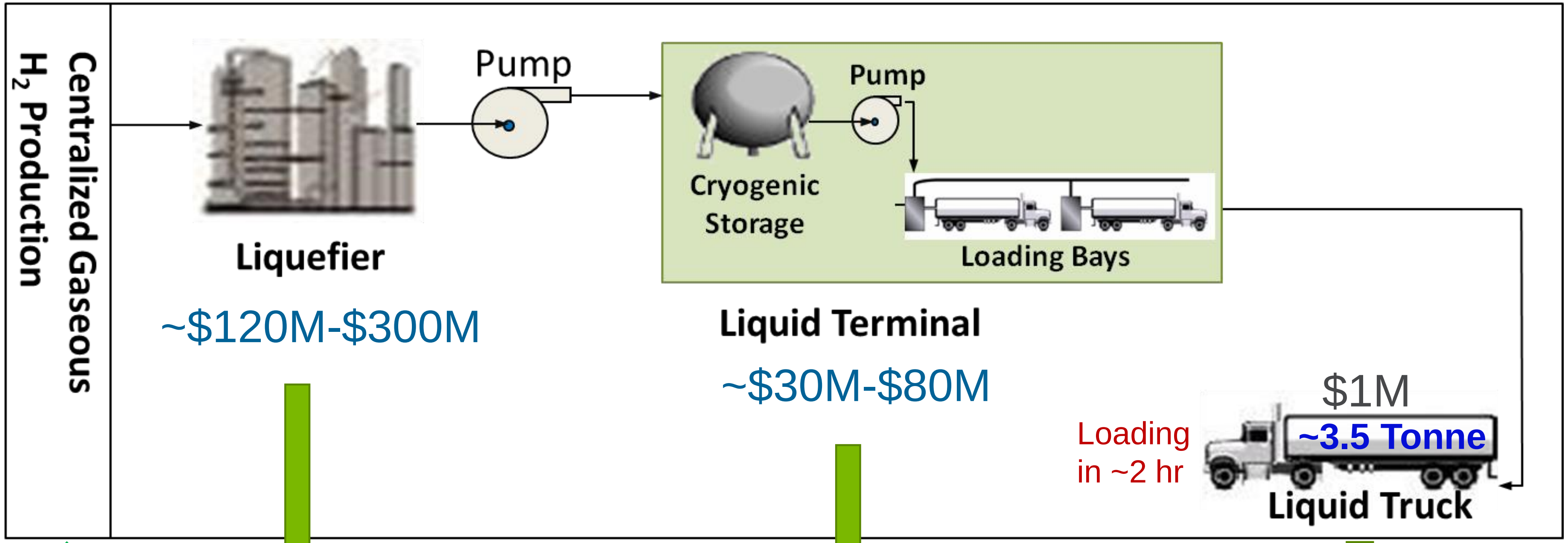
$100M-$300M

$2-$3/kg$_{H2}$

$0.5-$1/kg$_{H2}$.100mi

Total delivery cost $3 : $4 / kg$_{H2}$

Cost contribution of LH_2 delivery



30-100 MT/day

~\$2-\$2.5/kg_{H2}

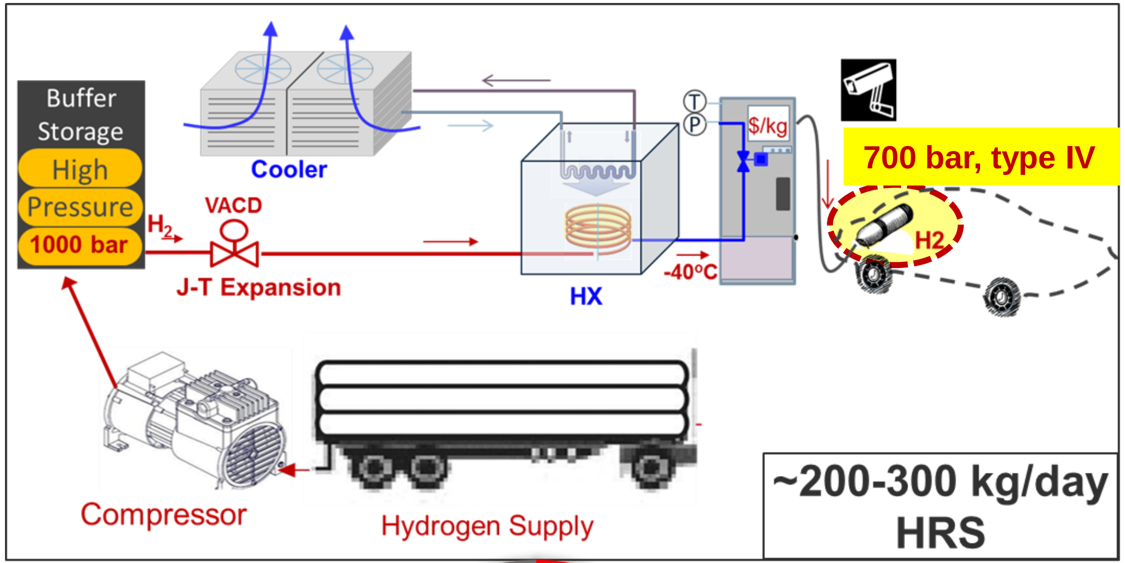
~\$0.3/kg_{H2}

~\$0.3/kg_{H2}.100mi

Total T&D cost \$2.5 : \$3 / kg_{H2}

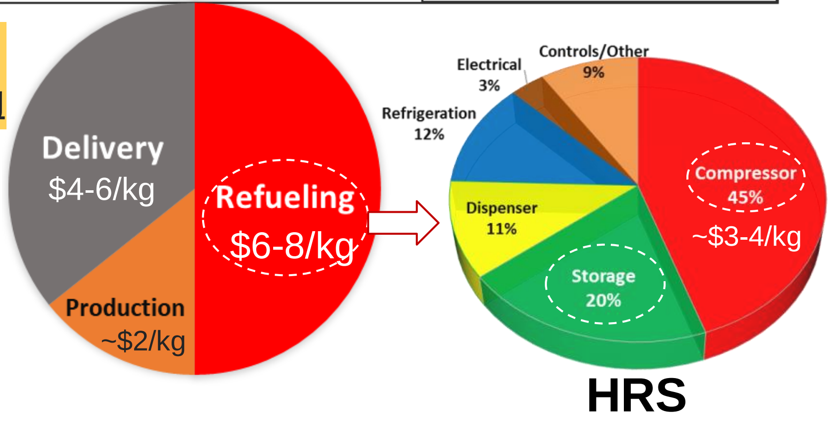
100 MT/day   30 MT/day

Cost of Hydrogen Delivery and Refueling for LD FCEVs is strongly driven by onboard storage requirement



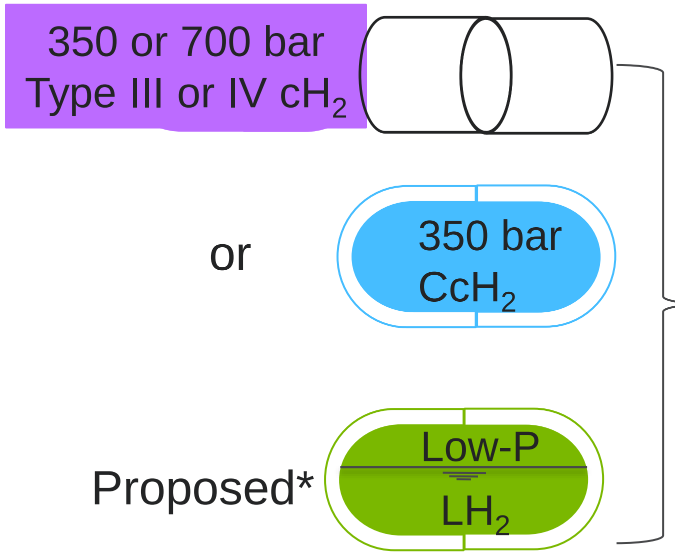
Today, hydrogen cost at the dispenser in CA is $15-$16/kg

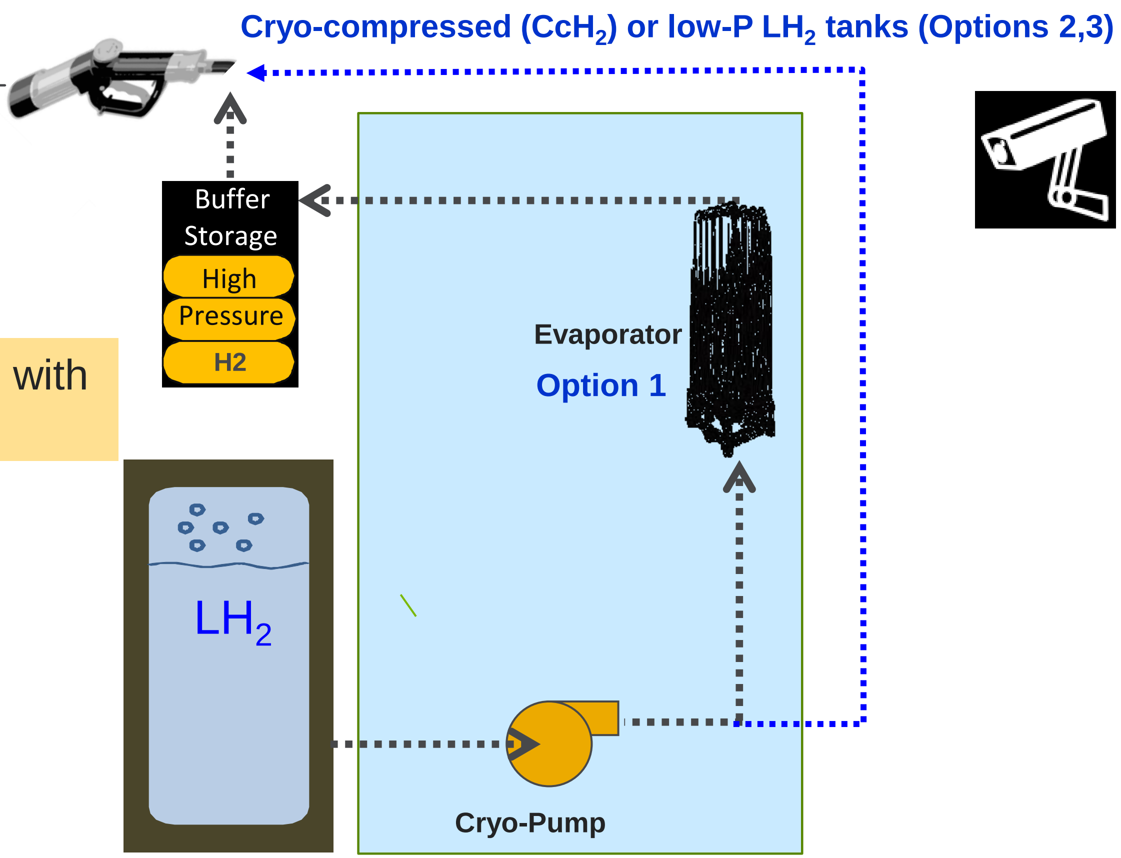
Bulk of H_2 cost is in delivery and refueling



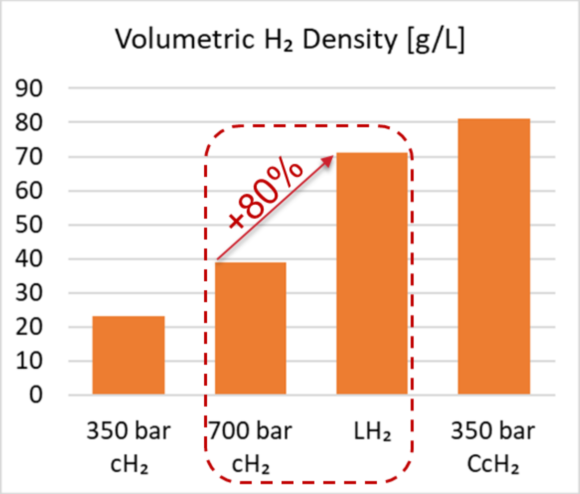
✓ HX: Heat Exchange	✓ VACD: Variable Area Control Device
✓ J-T: Joule-Thomson	✓ CA: California

Versatile refueling configuration options with LH_2 delivery



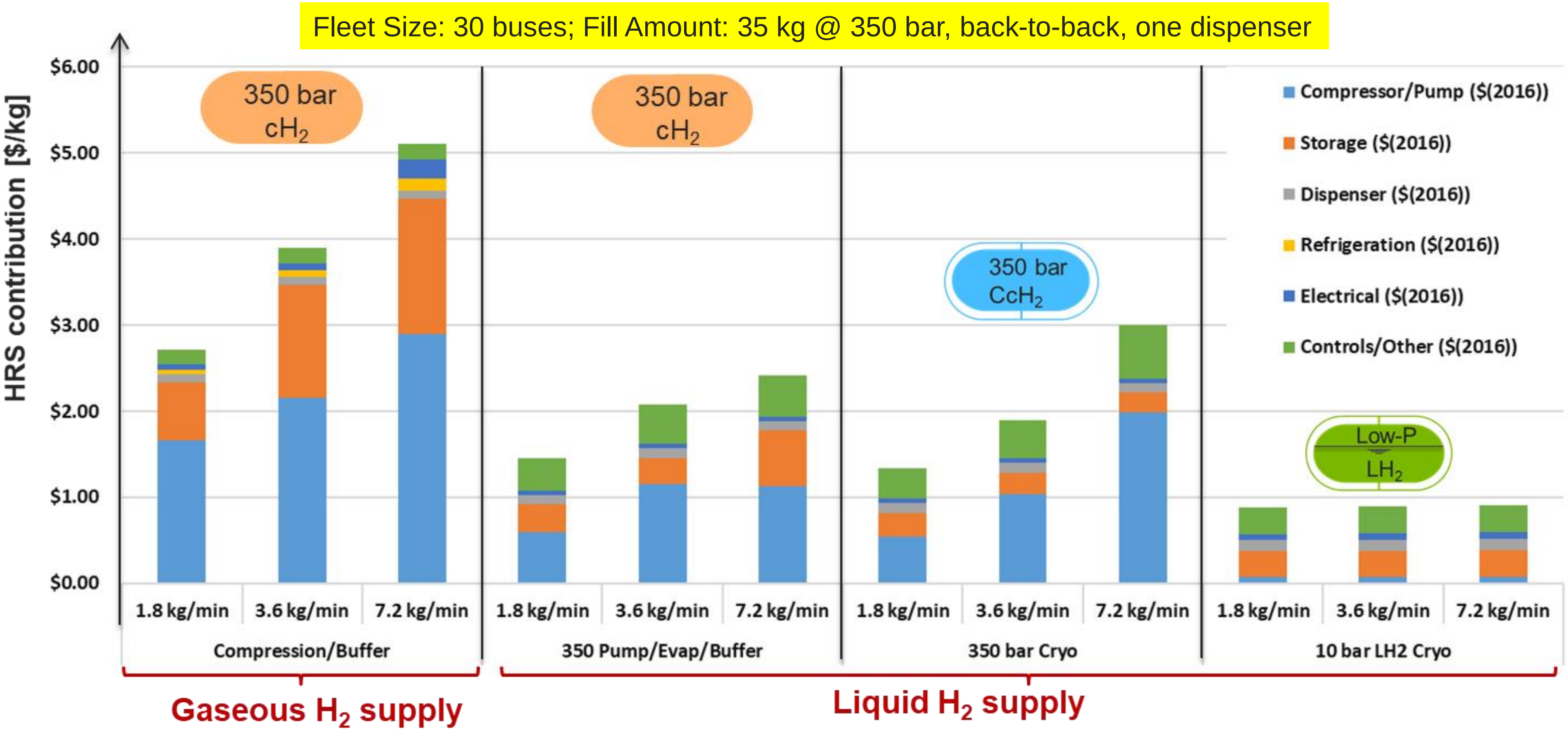


*Dormancy may be less of an issue with a predictable duty cycle of M/HDVs



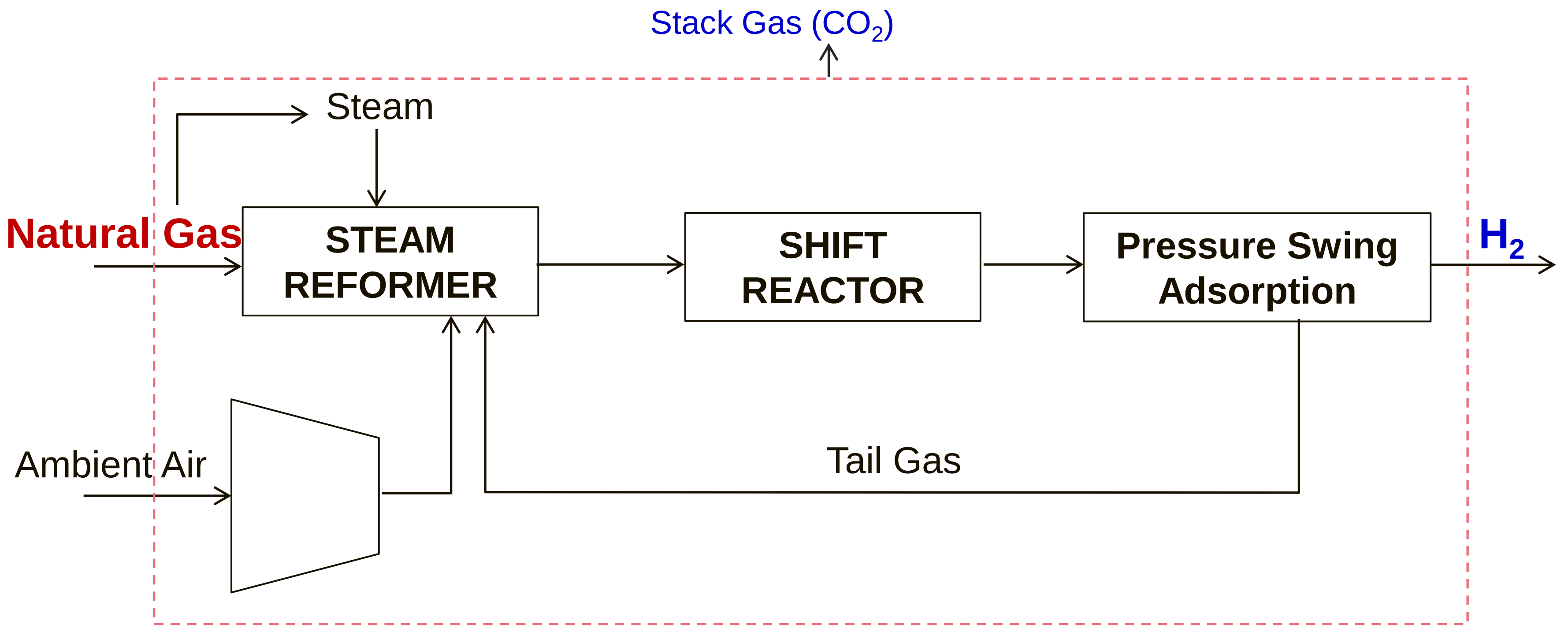
- ✓ LH_2: Liquid Hydrogen
- ✓ CcH_2: Cryo-compressed hydrogen
- ✓ cH_2: compressed hydrogen
- ✓ Low-P: Low Pressure (<10 bar)

Compression and pumping dominate refueling cost for high-pressure tanks



- ➢ Liquid supplied stations can handle faster fills with less cost increase compared to gaseous supply
- ➢ Cost of H_2 delivered to the station is additional

Hydrogen production today is mainly from NG SMR



✓SMR: Steam Methane Reforming
✓NG: Natural gas
✓LHV: Lower Heating Value
✓WTW: Well-To-Wheels
✓E10: 10% ethanol in gasoline (by vol.)
✓GGE: Gallon Gasoline Equivalent
✓ICEV: Internal Combustion Engine Vehicle

At 72% NG to H_2 energy efficiency (LHV-basis)

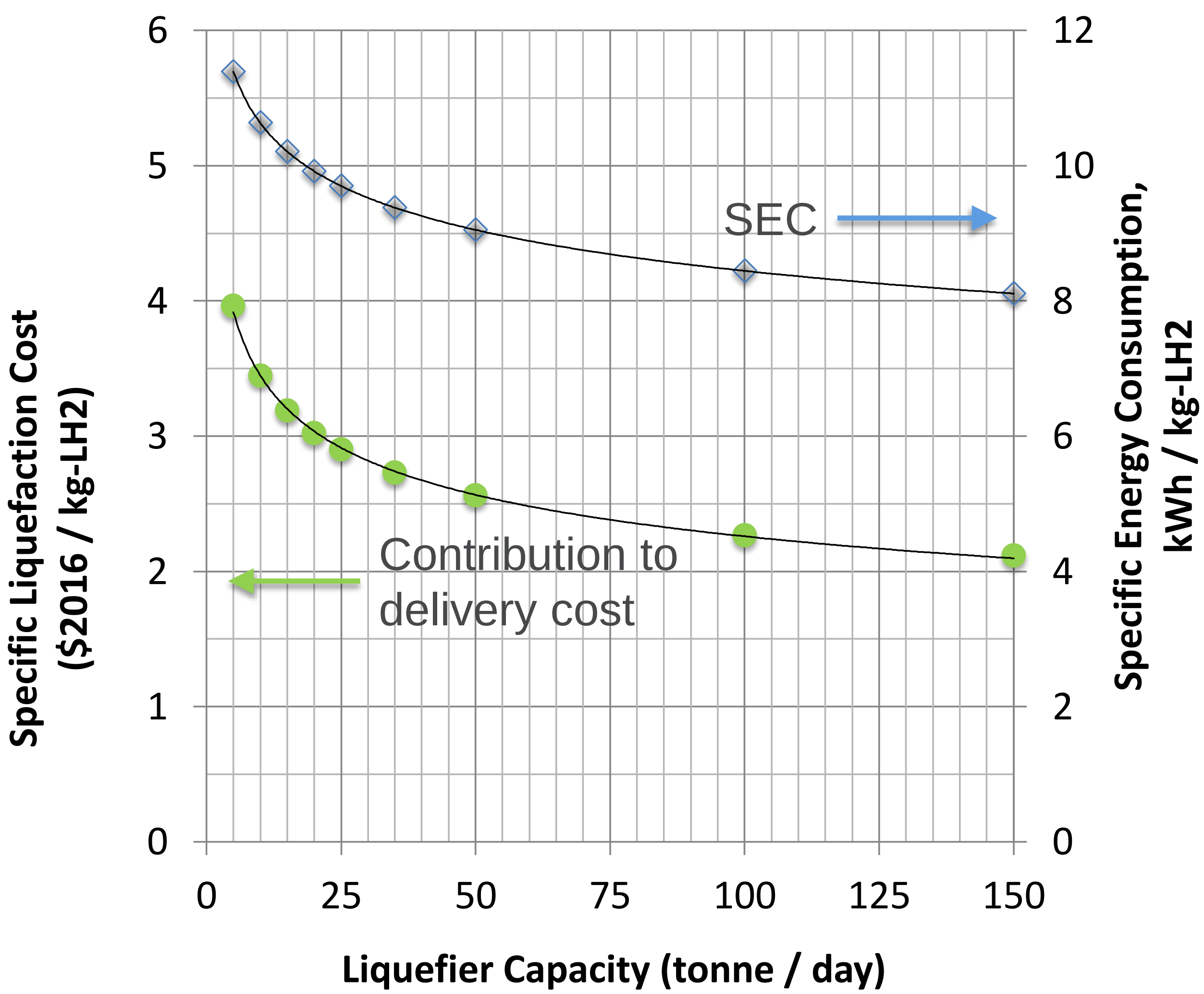
→ Well-to-plant gate GHG emissions = 10 $kg_{CO_{2e}}/kg_{H_2}$

HDSAM liquefaction model

- 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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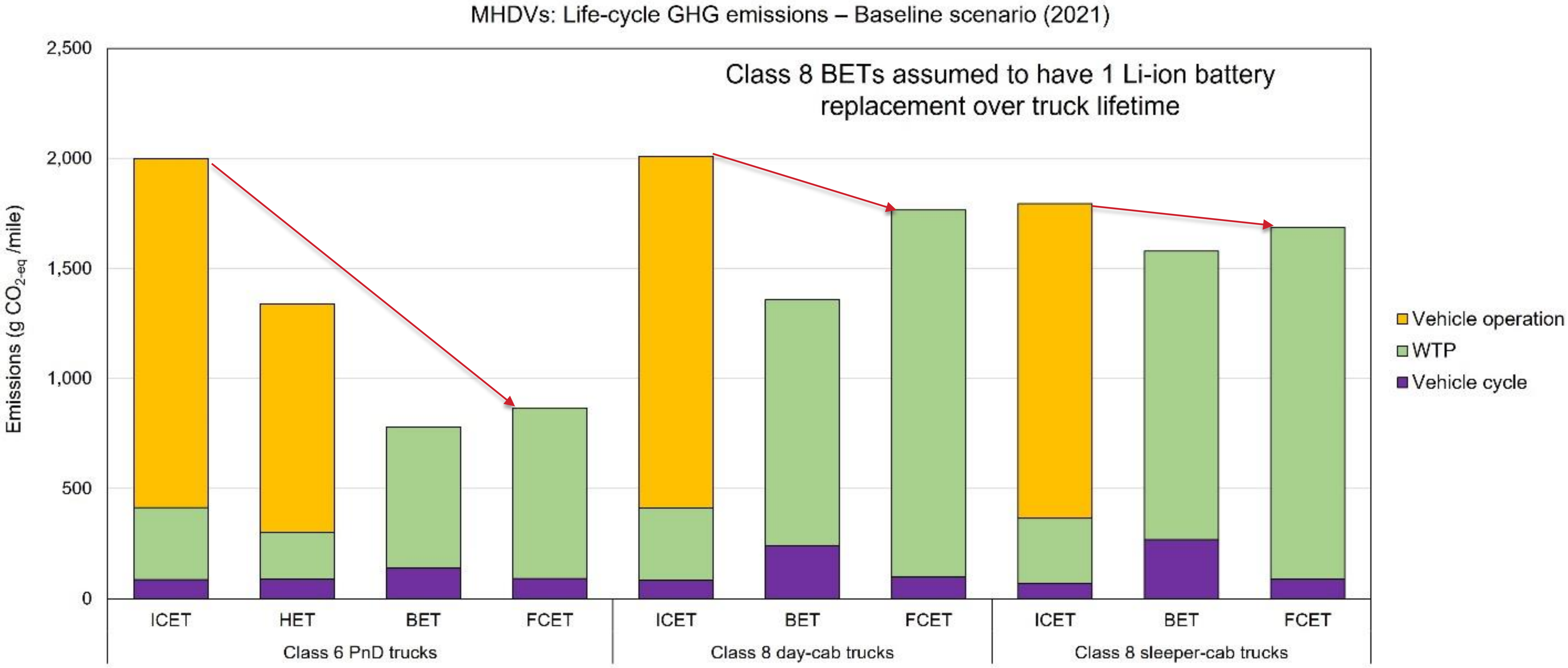
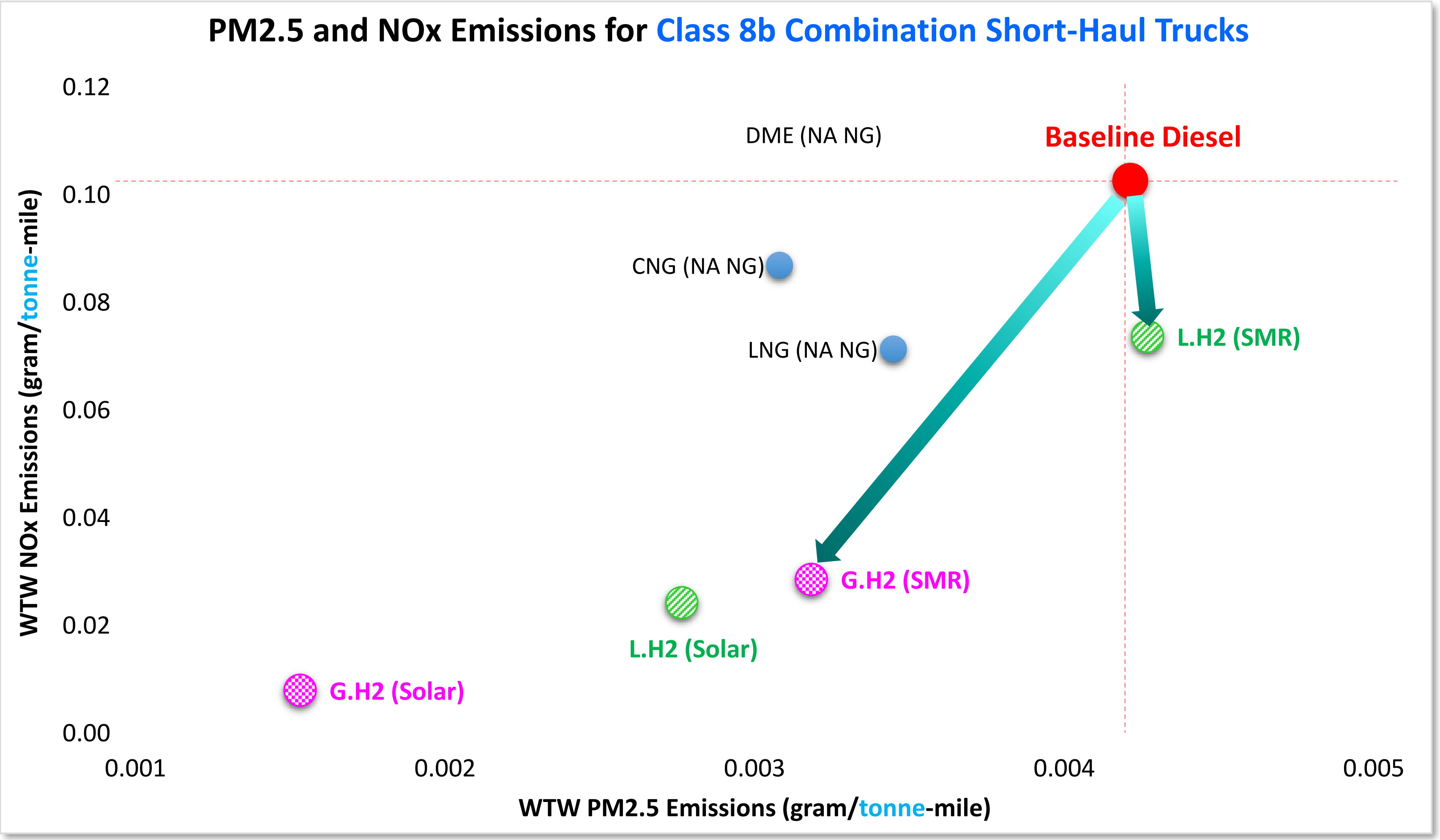
Complete C2G GHG emissions: gaseous supply (i.e., not including liquefaction GHG emissions)



Liquefaction: life-cycle criteria air pollutant emissions can also be significant



LH_2 impacts criteria air pollutant emissions depending on electricity grid mix used for liquefaction (US grid mix used for the above graph)

Thank You!

aelgowainy@anl.gov

efrank@anl.gov

Our models and publications are available at:

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

https://greet.es.anl.gov/publications