2020 DOE Hydrogen and Fuel Cells Program
Annual Merit Review

Impacts of Hydrogen On-board Storage Options on the Refueling Cost of Fuel Cell Heavy Duty Vehicles

Amgad Elgowainy (PI) and Krishna Reddi
Argonne National Laboratory

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SA170

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Overview

Timeline

- Start: October 2019
- End: Determined by DOE
- % complete (FY19): 80%

Barriers to Address

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

Budget

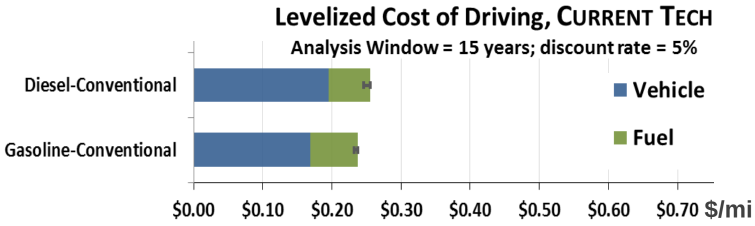
- Funding for FY20: $100K

Partners/Collaborators

- U.S.DRIVE: Hydrogen Interface Taskforce (H2IT)

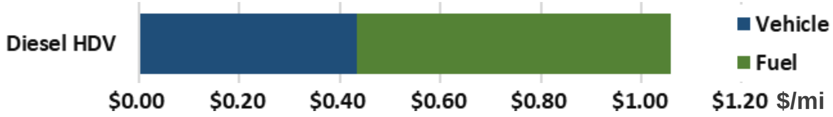
Fuel cost contribution to LCOD is much higher than vehicle cost in most M/HDV applications - Relevance/Impact

- ✓*Mainly due to high daily VMT and low fuel economy of M/HDVs*
- ✓*Opposite to LCOD of LDVs where vehicle cost dominates fuel cost*



LDVs, https://greet.es.anl.gov/publication-c2g-2016-report

Average Marginal Costs in 2018	[$/mi]
Fuel Costs [$3.18/gal in 2018]	$0.433
Truck/Trailer Lease or Purchase Payments	$0.265



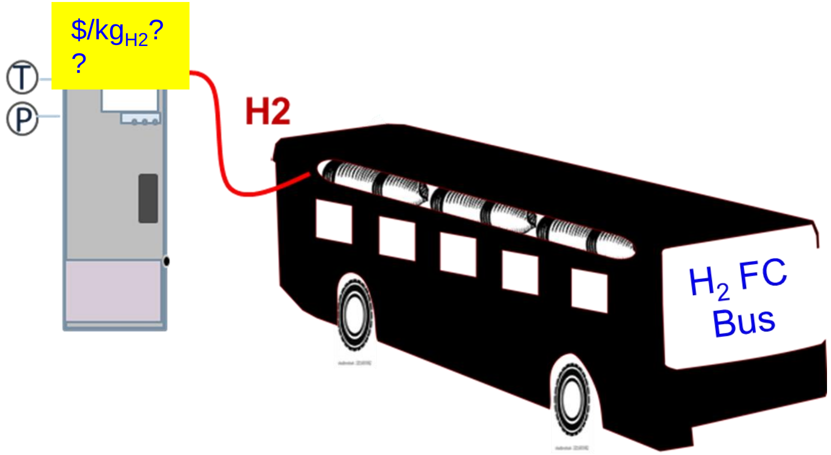
https://truckingresearch.org/atri-research/operational-costs-of-trucking/

	Passenger Car		Line Haul HDV	
	Gasoline ICEV	**H_2 FCEV**	**Diesel ICEV**	**H_2 FCEV**
Fuel Economy	25 mpgg	60mi/kg (~60 mpgge)	6 mpgd	7 mi/kg (6 mpgde)
Fuel Economy Ratio	**2.4**		**1.0**	
Equivalent Fuel Cost	**$2/gal**	**$4.8/kg**	**$2/gal**	**$1.8/kg**
	$3/gal	**$7.2/kg**	**$3/gal**	**$2.7/kg**
	$4/gal	**$9.6/kg**	**$4/gal**	**$3.6/kg**

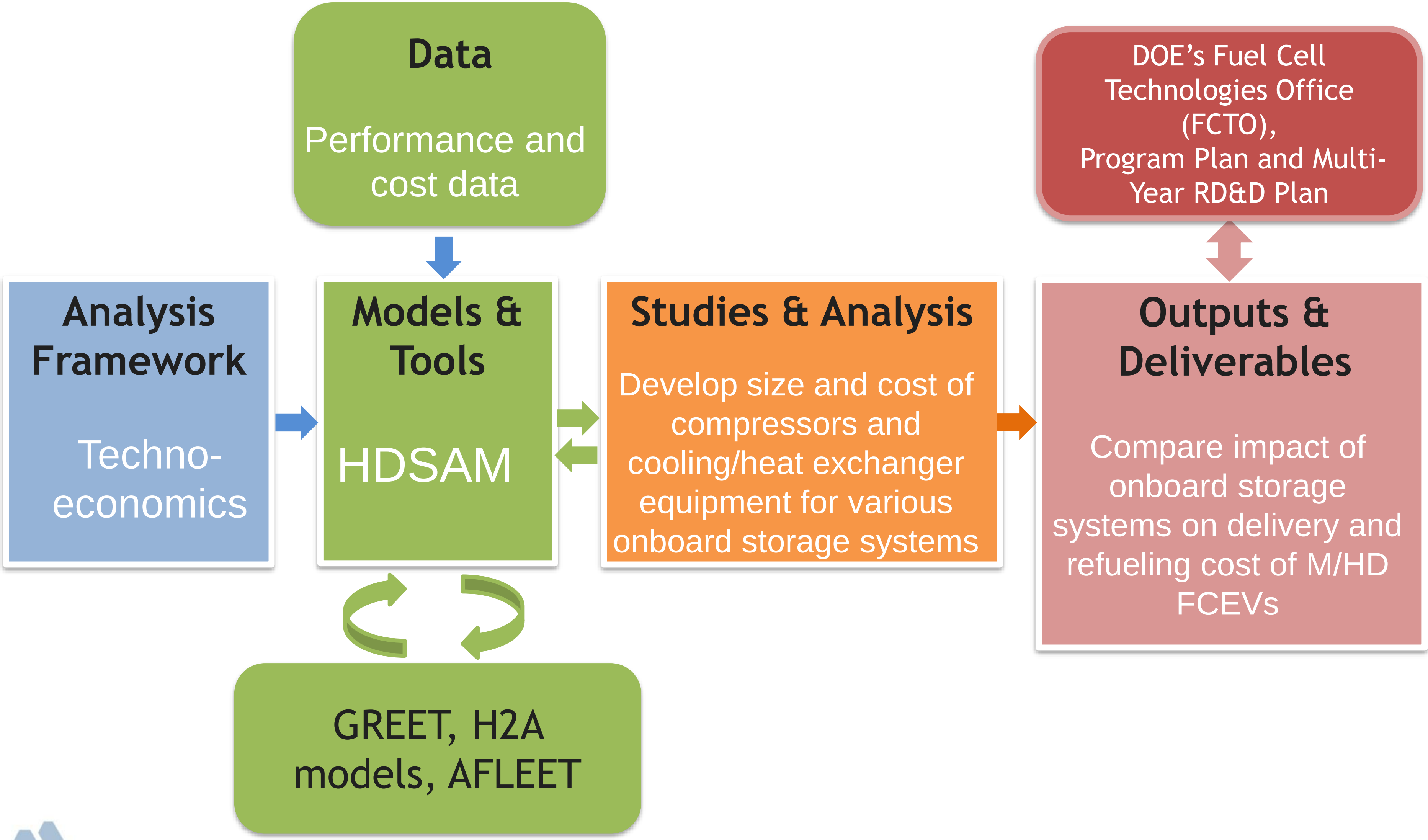
✓LCOD: Levelized Cost of Driving
✓M/HDV: Medium- and Heavy-Duty Vehicle
✓VMT: Vehicle Miles Travelled
✓LDV: Light-Duty Vehicle
✓C2g: Cradle-to-Grave
✓FCEV: Fuel Cell Electric Vehicle

Motivation and objective for examining fueling cost of FC HDVs – Relevance/Impact

- Fuel cost for M/HDVs dominates LCOD due to low fuel economy and high VMT
  - ➢ Hydrogen cost [\$/kg] needs to be much lower for fuel cell M/HDVs compared to light duty FCEVs
- Hydrogen refueling station (HRS) cost for heavy duty FCEVs is significantly different from HRS of light duty FCEVs
  - ➢ With respect to tank type, fueling pressure, fill amount, fill rate, fill strategy, precooling req., etc.
- Evaluate impacts of key market, technical, and economic parameters on refueling cost [\$/kg$_{H2}$] of heavy-duty fuel cell (FC) vehicles
  - ✓ Evaluate fuel cell bus fleet as a surrogate for other M/HDVs



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



Data

Performance and cost data

DOE's Fuel Cell Technologies Office (FCTO), Program Plan and Multi-Year RD&D Plan

Analysis Framework

Techno-economics

Models & Tools

HDSAM

Studies & Analysis

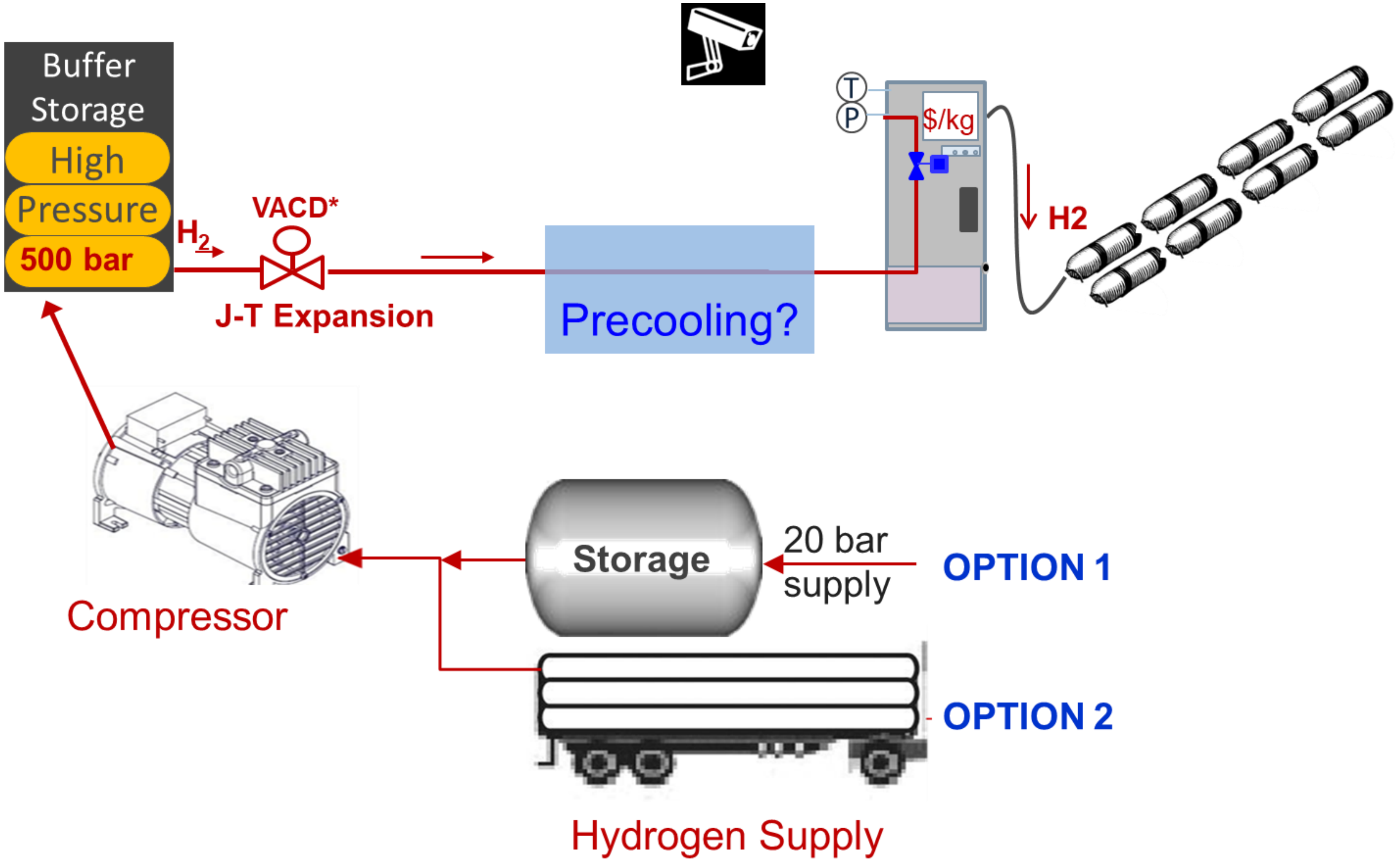
Develop size and cost of compressors and cooling/heat exchanger equipment for various onboard storage systems

Outputs & Deliverables

Compare impact of onboard storage systems on delivery and refueling cost of M/HD FCEVs

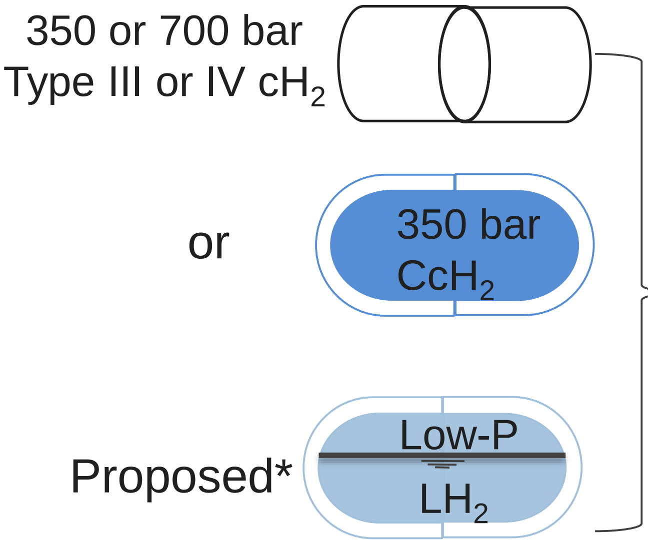
GREET, H2A models, AFLEET

Refueling configuration options with gaseous H_2 supply - Approach

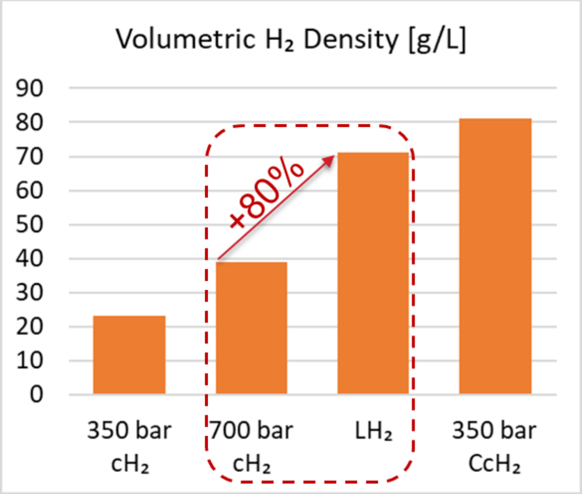


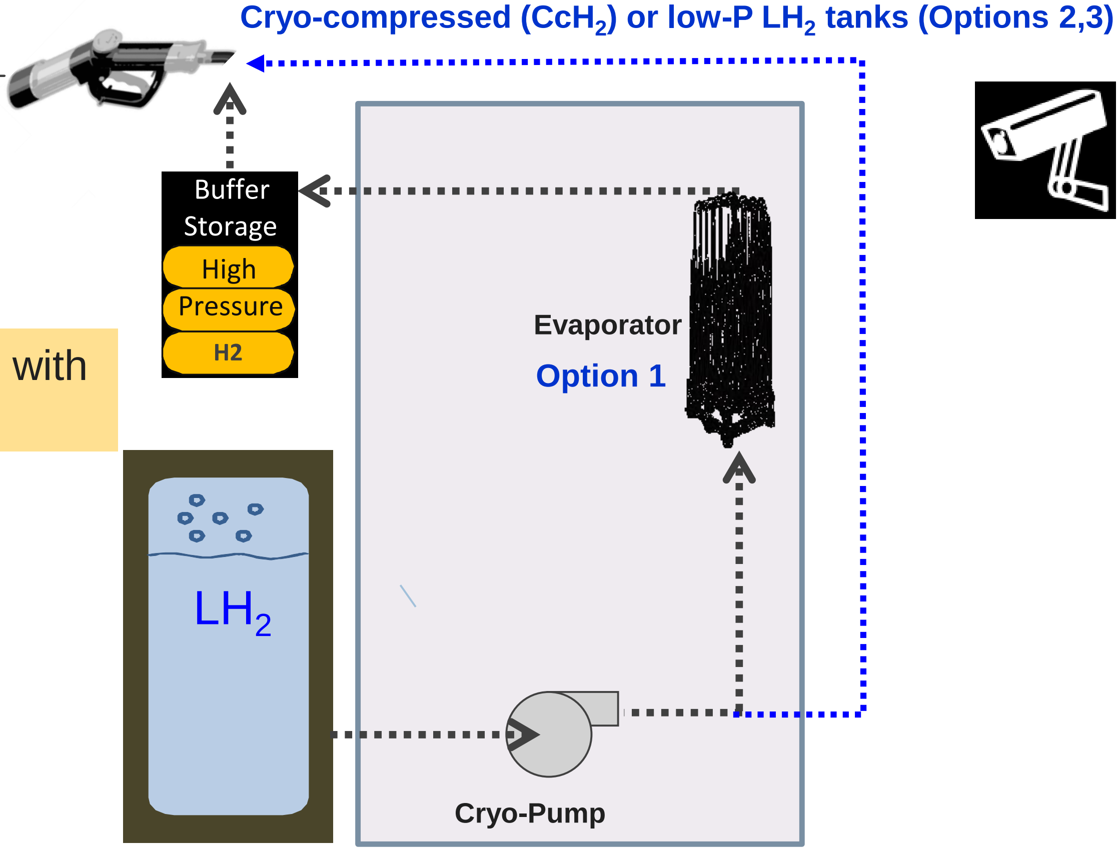
*variable area control device

Refueling configuration options with LH_2 delivery - Approach



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

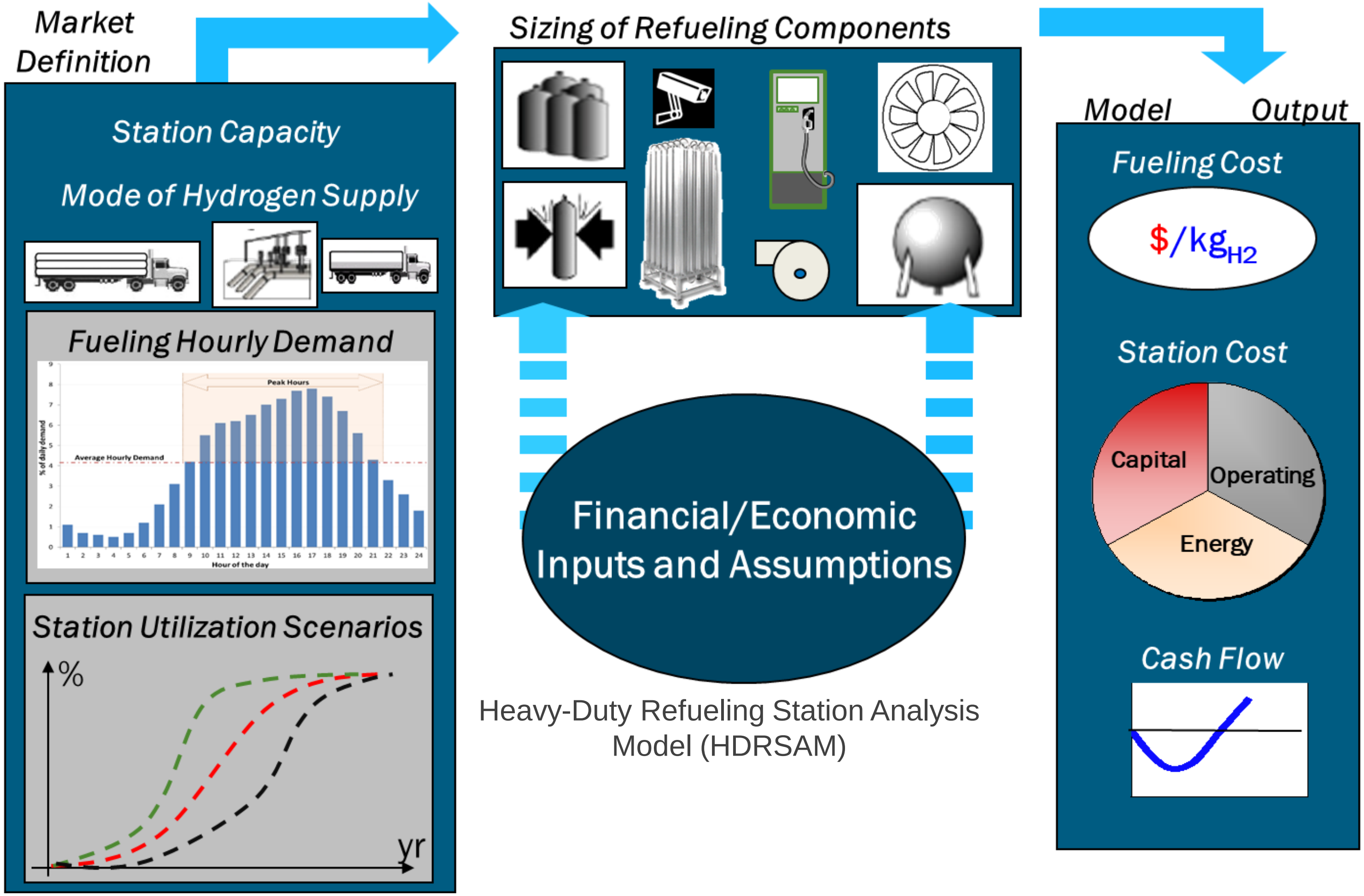




- ✓ LH_2: Liquid Hydrogen
- ✓ CcH_2: Cryo-compressed hydrogen
- ✓ cH_2: compressed hydrogen
- ✓ Low-P: Low Pressure (<10 bar)

Developed a techno-economic model for evaluating refueling cost of FC HDV fleet - Approach

- Systematically examines impact of various parameters



Market Definition

Station Capacity

Mode of Hydrogen Supply

Fueling Hourly Demand

Station Utilization Scenarios

Sizing of Refueling Components

Financial/Economic Inputs and Assumptions

Heavy-Duty Refueling Station Analysis Model (HDRSAM)

Model Output

Fueling Cost

$\$/kg_{H2}$

Station Cost

Cash Flow

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

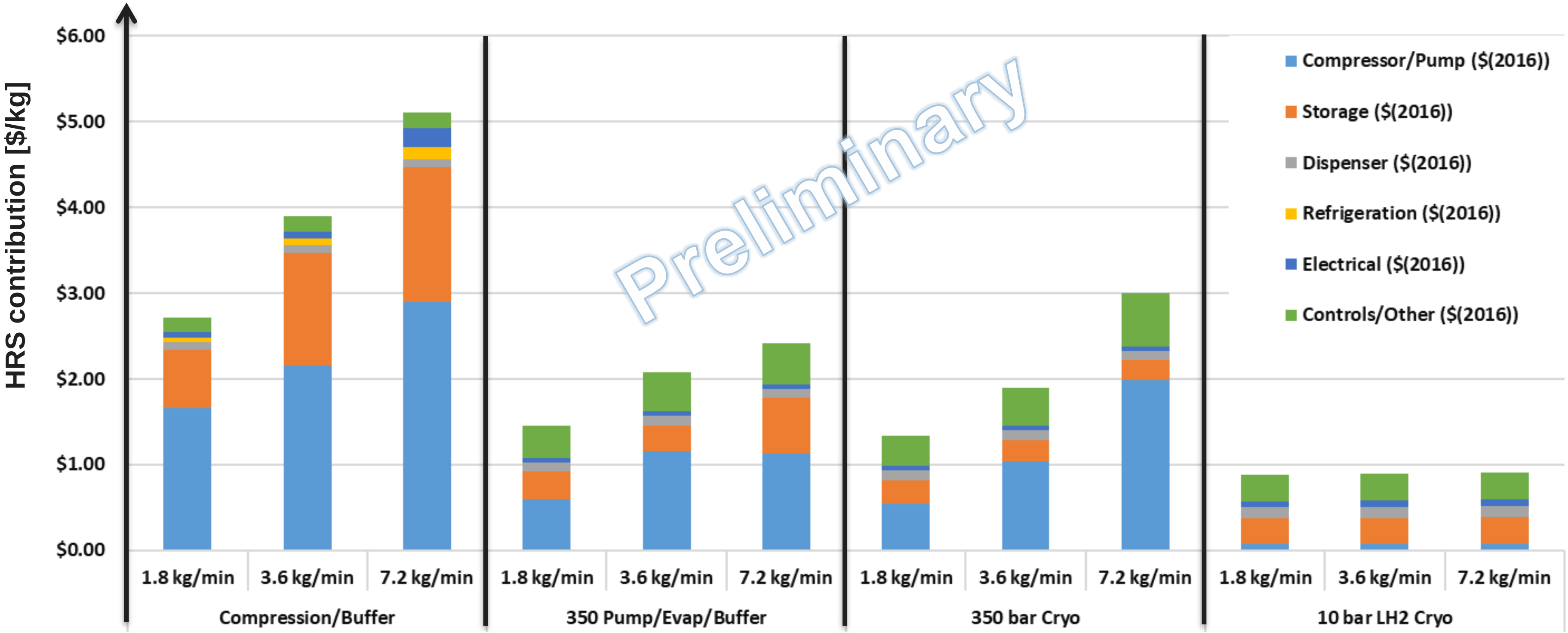
Parameters affecting fueling station cost - Approach

- Market parameters:
  - Fleet size (10, 30, 50, 100 buses)
  - Hydrogen supply (20 bar gaseous, LH_2 tanker, tube trailer)
  - Market penetration (production volume of refueling components, i.e., low, med, high)
- Technical parameters:
  - Tank type (III and IV cH_2, CcH2, low-pressure LH_2 tanks)
  - Refueling pressure (350 bar and 700 bar for gaseous cH_2, 350 bar CcH_2 and 10 bar low-pressure LH_2 tanks)
  - Dispensed amount per vehicle (20 kg, 35 kg)
  - Fill rate (1.8, 3.6, 7.2 kg/min)
  - Fill strategy (back-to-back, staggered, number of dispensers)
  - SAE TIR specifies fueling process rates and limits (not a protocol)
- Financial parameters:
  - 10% IRR
  - 20-year project life

- Parameters in red color are defaults for parametric analysis

Compression and pumping dominate refueling cost for high-pressure tanks – *Accomplishment*

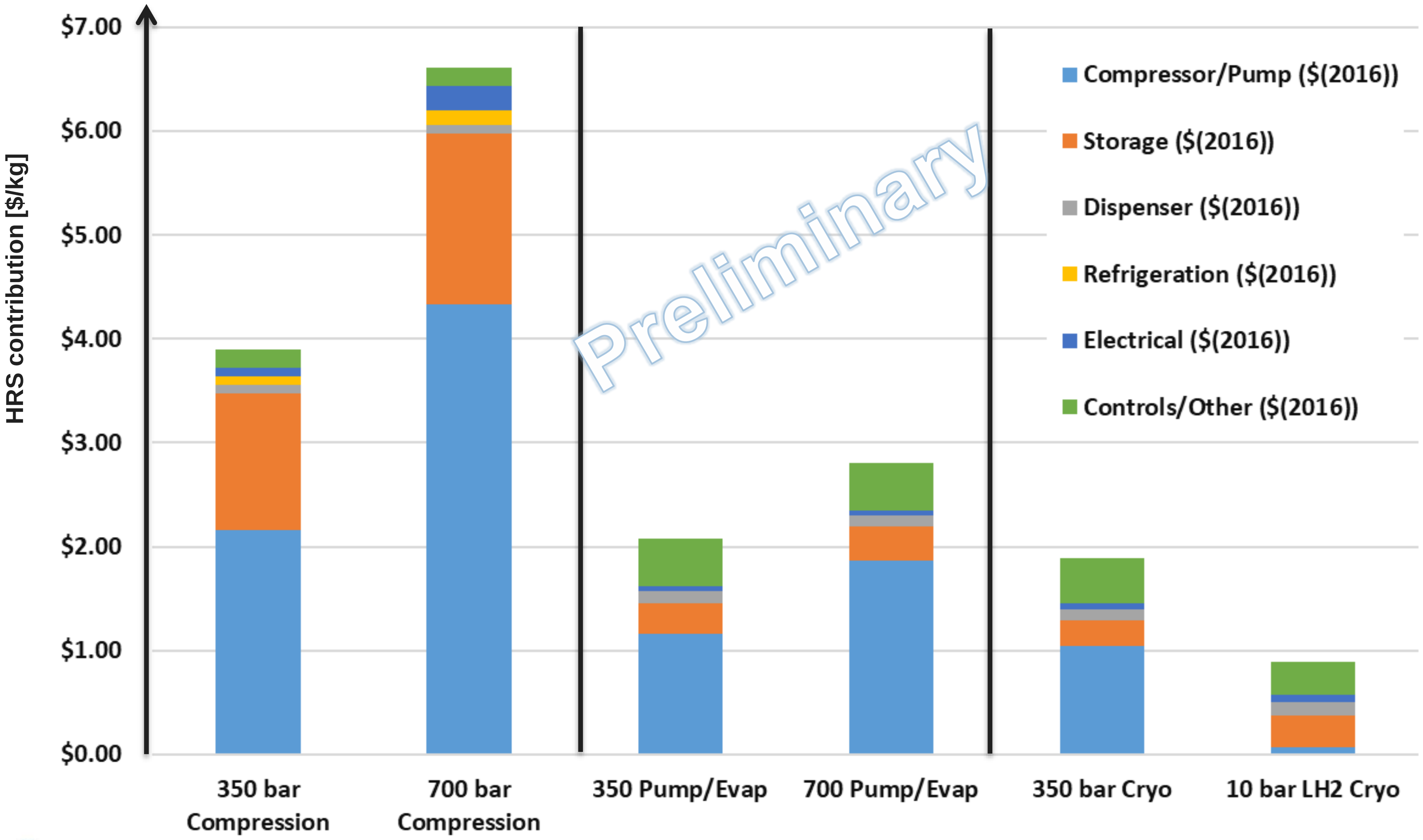
Fleet Size: 30 buses; Fill Amount: 35 kg @ 350 bar, back-to-back, one dispenser



- Faster fills require higher capacity equipment and result in higher cost
- Liquid supplied stations can handle faster fills with less cost increase
- Low-P LH_2 can reduce fueling cost contribution to < $\$1/kg_{H2}$

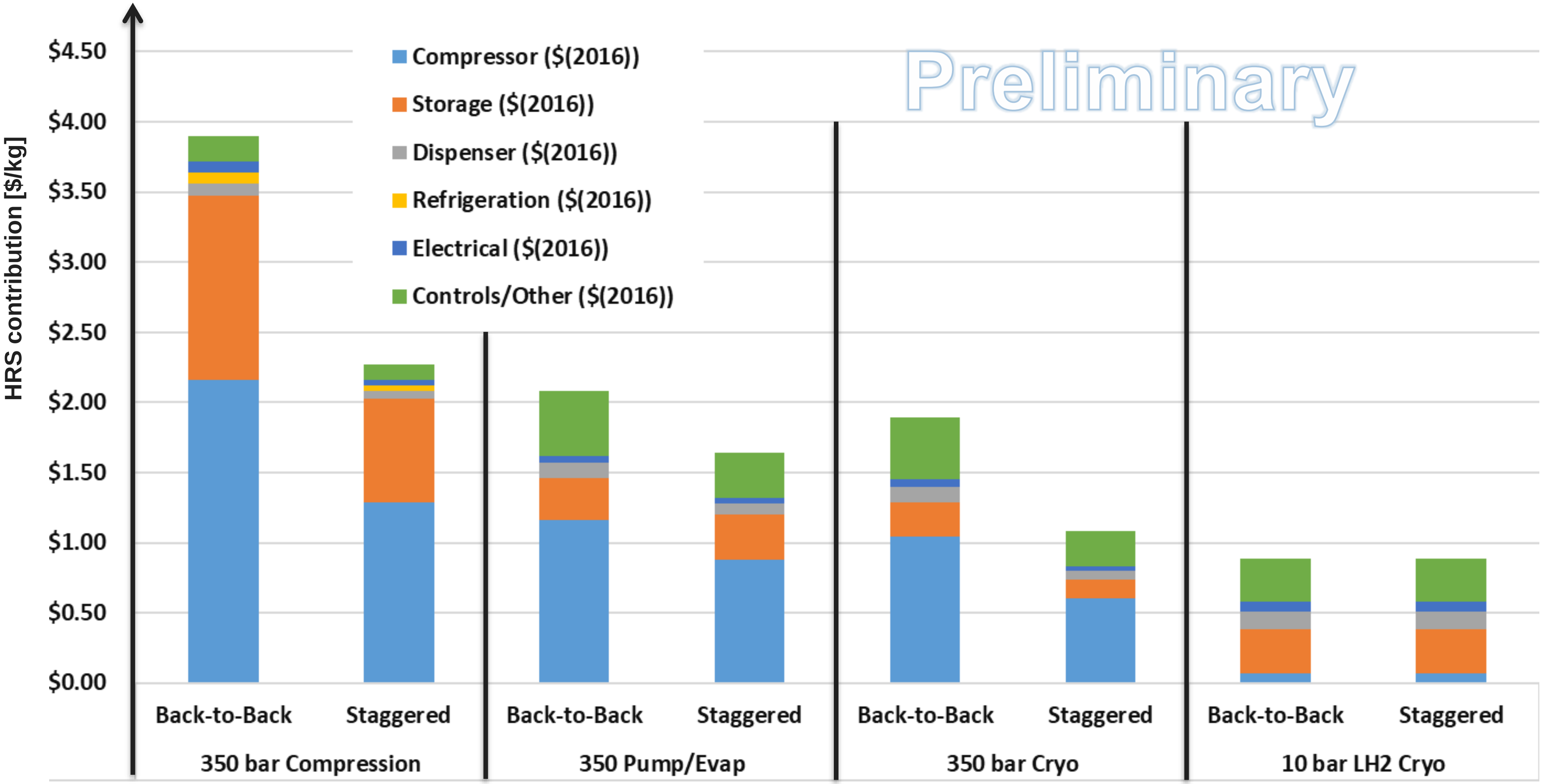
700 bar tanks dramatically increase fueling cost, especially with gaseous supply – Accomplishment

Fleet Size: 30 buses; Fill Amount: 35 kg @ 3.6kg/min, back-to-back, one dispenser



Staggered fueling reduce fueling cost - Accomplishment

Fleet Size: 30 buses; Fill Amount: 35 kg @ 350 bar and 3.6 kg/min, one dispenser



- ➢Staggered fueling is likely with commercial stations rather than fleet service stations

Cost estimates of H_2 supply to refueling station (near-term) - Accomplishment

Note: H_2 production/transportation costs are additional to refueling cost

- Cost of liquid H_2 delivered to refueling station (3.5-4 MT payload), 100-500 miles transportation distance:
  - $4-6/kg_H$_2$
- Cost of onsite water-electrolysis H_2 production + compression:
  - $6-10/kg_H$_2$
- Cost of onsite SMR H_2 production + compression:
  - $3-5/kg_H$_2$
  - Steady operation desirable
    - ✓ Additional storage cost may be required

Preliminary

Energy penalty and CO_2 emissions are critical for environmental impacts of H_2 liquefaction - Accomplishment*

Preliminary

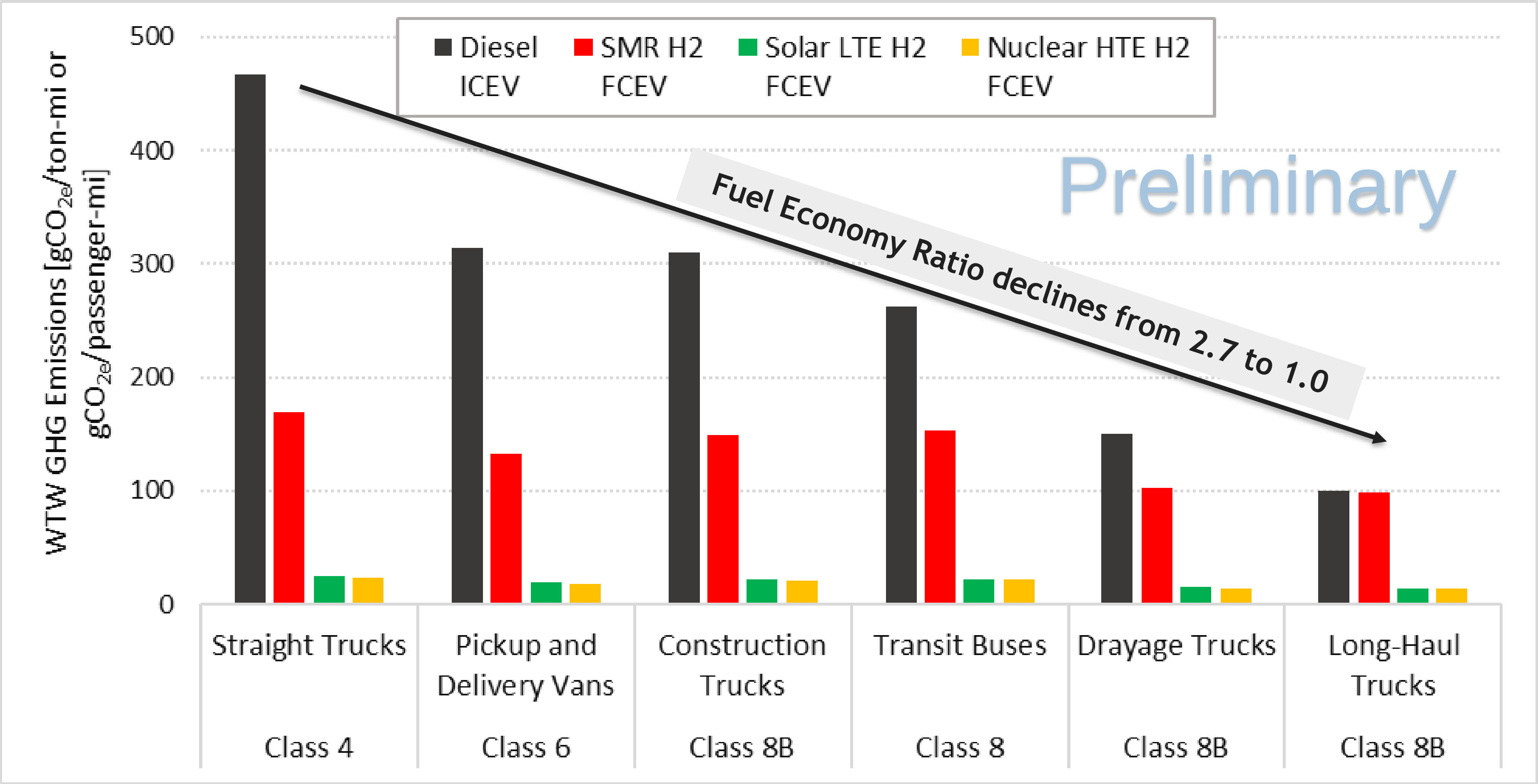
Region	Liquefaction Capacity (MT/day)
California	30
Louisiana	70
Indiana	30
New York	40
Alabama	30
Ontario	30
Quebec	27
Tennessee	6
Total	263

→ Liquefaction CO_2 emissions*= 0-12 $kg_{CO_{2e}}/kg_{H_2}$ (6 with US mix)

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

*12 $kWhe/kg_{H2}$

Renewable and nuclear hydrogen enable substantial GHG emissions reductions in different M/HDV types and vocations - *Accomplishment*



Fuel economy ratio impacts WTW GHG emissions of SMR-H_2 relative to diesel

✓WTW: Well-To-Wheels ✓GHG: Greenhouse Gas ✓SMR: Steam Methane Reforming

Summary – Accomplishment

- Faster fills require higher capacity equipment and result in higher fueling cost
  - ✓ Especially with high capacity onboard gaseous storage (e.g., filling 700 bar tanks with 100 kg @10 kg/min)
- Lower refueling cost of HD FCEV fleet compared to refueling LDVs if appropriate onboard storage is adopted
- LH_2 supply for the refueling of Type IV cH_2, CcH_2 and low-P LH_2 tanks provides much lower HRS cost compared to stations sourcing gaseous H_2
  - ✓ Additional liquefaction capacity needs to be built
  - ✓ Low-carbon electricity is crucial for low-carbon liquid hydrogen supply
  - ✓ High-pressure cryopumps for CcH_2 need R&D to reduce their cost
  - ✓ Developing low-pressure LH_2 tanks can reduce fueling cost contribution to <$1/kg
  - ✓ Note: cost of H_2 supply is additional and vary by source, technology, distance and scale
- Strong economies of scale can be realized with fleet size and fill amount (impacting station demand/capacity)
  - ✓ ~$0.5/kg_$H_2$ station cost for 100 FC bus fleet with today's equipment cost

Collaborations and Acknowledgments

- Mike Veenstra, Ford Motor Company, provided technical information and general guidance and support
- Jesse Adams (DOE) provided technical information and general guidance and support
- U.S.DRIVE Delivery and Storage Tech Teams

Future Work

- Refine cost estimate of high-throughput equipment needed for fast fueling of M/HD FCEVs
  - e.g., dispensers, high throughput pumps, etc., currently unavailable
- Examine impact of LH_2 boiloff on hydrogen delivery and fueling cost
- Expand system boundary to include delivery + refueling cost for consistent comparison
- Incorporate HDV fleet fueling model in HDSAM
  - Conduct independent model review by subject matter experts
  - Release updated HDSAM with new HDV module
- Expand energy and emissions analysis (life cycle) to evaluate other M/HD FCEV classes and vocations
  - Conduct regional analysis
- Document data and analysis in peer-reviewed publication

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

Project Summary

- **Relevance**: On-board hydrogen storage systems can have large impact on refueling cost of M/HD fuel cell vehicles
- **Approach**: Develop new model to evaluate refueling cost for various H_2 onboard systems
- **Collaborations**: Collaborated with consultants and experts from industries and across US DRIVE technical teams
- **Technical accomplishments and progress**:
  - Faster fills require higher capacity equipment and result in higher fueling cost
  - Lower refueling cost of HD FCEV fleet compared to refueling LDVs can be achieved if appropriate onboard storage is adopted
  - LH_2 supply for fueling Type IV cH_2, CcH_2 and low-P LH_2 tanks provides much lower HRS cost compared to stations sourcing gaseous H_2
  - Low-carbon electricity is crucial for low-carbon liquid hydrogen supply
  - Developing low-pressure LH_2 tanks can reduce fueling cost contribution to <$1/kg
- **Future Research**:
  - Refine cost estimate of high-throughput equipment needed for fast fueling of M/HD FCEVs
    - e.g., high-flow dispensers, high throughput pumps, etc.
  - Examine impact of LH_2 boiloff on hydrogen delivery and fueling cost
  - Expand system boundary to include delivery + refueling cost for consistent comparison
  - Incorporate HDV fleet fueling model in HDSAM
  - Expand energy and emissions analysis to evaluate other M/HD FCEV classes and vocations
  - Document data and analysis in peer-reviewed publication

aelgowainy@anl.gov

Response to Reviewers' Comments from 2019 AMR

This is certainly useful analysis, and the project could benefit from a broader consideration of the supply chain to assess the key challenges that need to be addressed. Examples include (1) upstream supply and distribution (local vs. centralized production, cost of liquefaction, hydrogen delivery options and costs, etc.); and (2) onboard vehicle storage implications (new technology development required, cost, storage durability, storage volumetric and gravimetric density, etc.)

- We agree that the overall DOE program must address all these challenges. We expanded the scope of our analysis to include new vehicle classes, multiple hydrogen pathways, and new onboard storage options. We also included environmental life cycle analysis to show the trade off between the economic and environmental impacts of various hydrogen infrastructure pathway options.

The project has identified avenues to reduce the cost of dispensed hydrogen, which is a key barrier to fuel cell electric vehicle adoption. However, additional work is needed to understand the impact on total cost of ownership. The project has largely met the analytical objectives established for the project.

- The scope the analysis was expanded to be based on the total cost of ownership (TCO), and thus shifted the focus from light-duty vehicles to medium-and heavy-duty (M/HD) vehicles. For M/HD fuel cell vehicles, the fuel cost dominates the TCO, and thus reducing fuel cost at the dispenser is key to the successful deployment of fuel cell vehicles in the various M/HD vehicle classes and vocations.

Cost reduction for hydrogen compression, storage, and transport is crucial to reaching cost targets for dispensed hydrogen, so the work aligns strongly with Program goals. However, the lack of the cost impact of the onboard storage systems limits the ability to draw conclusions from this phase of the work.

- The purview of this analysis was limited to the hydrogen delivery infrastructure (i.e., not including vehicle cost). However, we expanded the scope of the analysis to include medium-and heavy-duty (M/HD) vehicles, where the TCO is dominated by fuel cost, thus the impact of the onboard storage cost on TCO is minimized. The analysis showed the strong impact of the hydrogen onboard storage type on fueling cost.