2017 DOE Hydrogen and Fuel Cells Program
Annual Merit Review

Hydrogen Refueling Analysis of Heavy-Duty Fuel Cell Vehicle Fleet

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PD 14

Overview

Timeline

- Start: FY 2007
- End: Determined by DOE
- % Complete (FY17): 70%

Barriers/Challenges

- Lack of hydrogen infrastructure options analysis
- Cost and efficiency of delivery components
- Lack of appropriate models and analytical capability
- Conduct unplanned studies and analyses

Budget

- FY16 Funding: $100K
- FY17 Funding: $150K
- 100% DOE funding

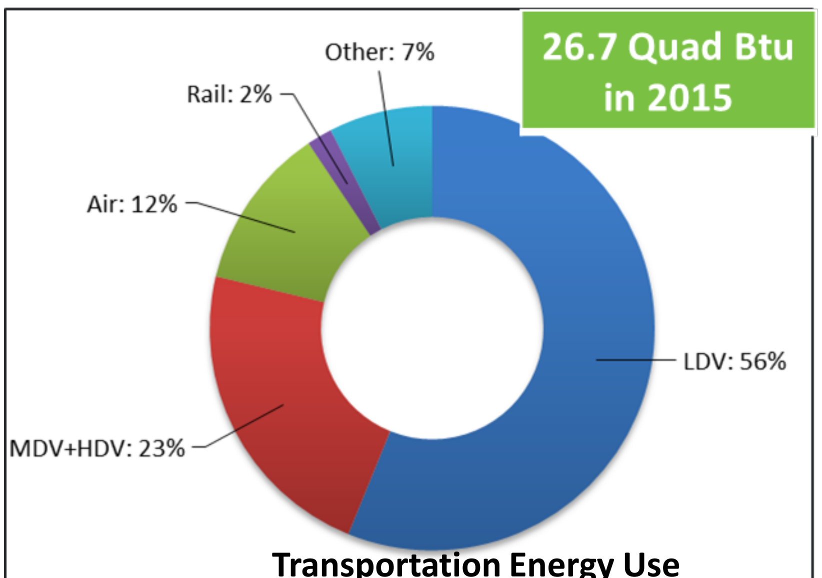
Partners and Collaborators

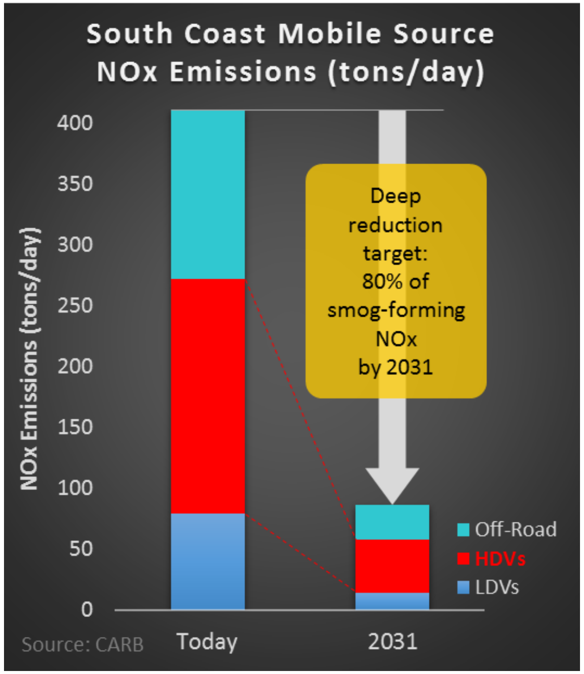
- Energy Technology Analysis LLC
- FuelScience LLC
- Boyd H2
- Industry Stakeholders

Relevance/Impact

The increasing importance of medium- and heavy-duty vehicles (MHDV) in transportation with respect to energy use and emissions

- MHDV is the second largest and fastest growing energy consumer in transportation, accounting for significant energy use and air emissions.
  - ➢ Energy share expected to grow to 30% of total transportation energy by 2040
- MHDV NOx and PM10 emissions comparable to LDV emissions (0.94 and 0.8 of LDV emissions in 2014, respectively)
- CA targets 80% reduction of mobile source NOx emissions by 2030 → role for ZEV HDV → Fuel cells for transit buses

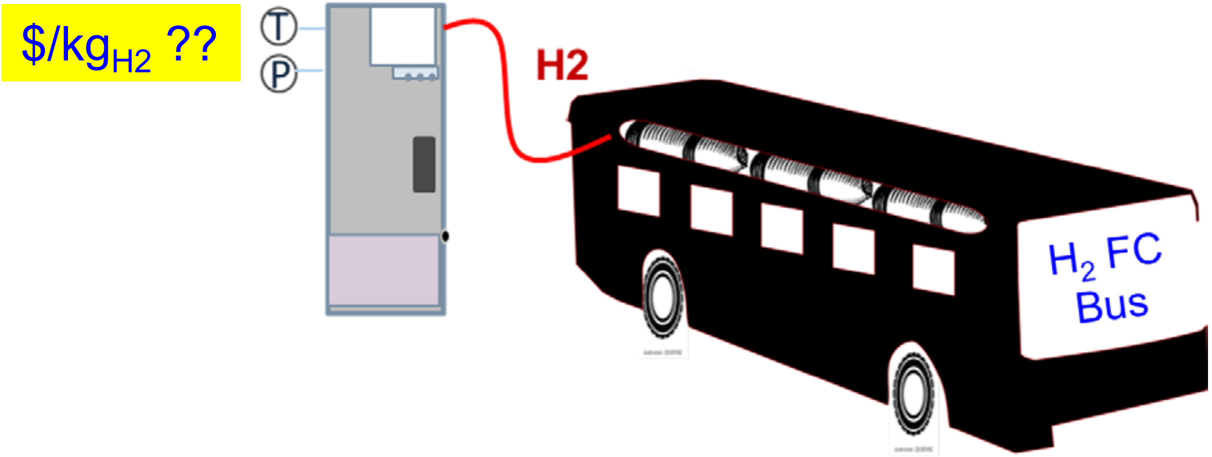




Relevance/Impact

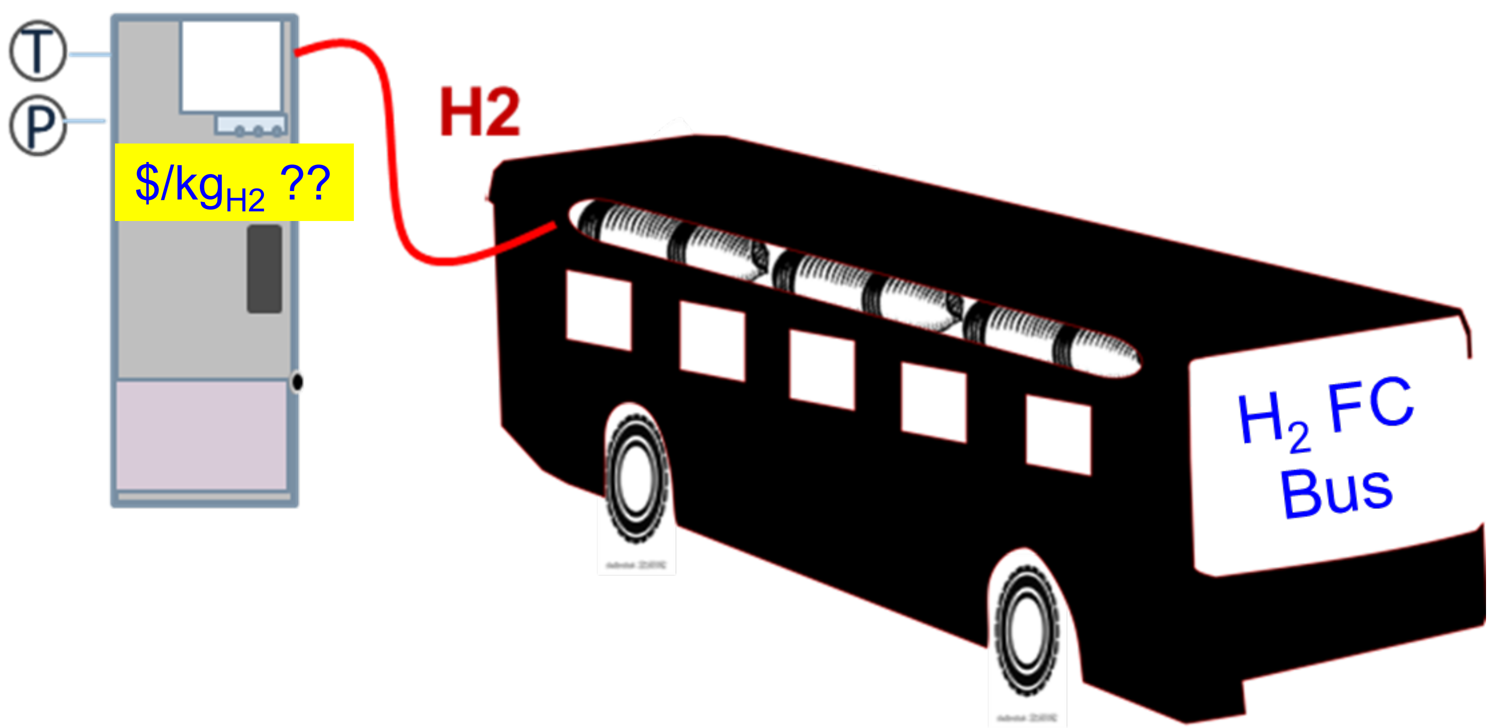
Fuel Cell Vehicles can address energy and emissions problems, but at what cost?

- Gap exists in the literature regarding HDV hydrogen fueling cost
  - Interest in station design and cost reduction potential with increased throughput
- Hydrogen fueling cost for HDV is different from LDV
  - With respect to fueling pressure, fill amount, fill rate, fill strategy, precooling requirement, etc.
- DOE and industry stakeholders seek evaluation of key parameters impacting hydrogen fuel cell HDV fueling cost
  - New modeling and analysis is needed to inform DOE of potential challenges to achieving cost competitiveness for fuel cell HDV applications



Objective

- Evaluate impacts of key market, technical, and economic parameters on refueling cost [$/kg_{H2}$]of heavy-duty fuel cell vehicles
  - ✓ Evaluate fuel cell buses as a surrogate for other HDVs



Develop a refueling model for hydrogen HDV fleet - Approach

- Systematically examine impact of various parameters

Station Type
- (•) Gaseous H2 station
- ( ) Liquid H2 station

Hydrogen Source
- ( ) Tube-trailer supply
- (•) 20 bar H2 supply

Fleet Size
Maximum # of Vehicle Fills per Day: 30

Dispensing Options to Vehicle Tank
- (•) 350 bar Cascade dispensing

Production volume for cost estimates (see table on right)
- (•) Low
- ( ) Mid
- ( ) High

Click Here To Calculate

Click Here To Save Results

Total Refueling Cost [$/kg]	**1.88**
Total Capital Investment	**$ 2,744,222**
Years to breakeven on investment	**7.33**

Capital [$/kg]	1.13
O&M less energy [$/kg]	0.42
Energy/Fuel [$/kg]	0.33

General Economic Assumptions

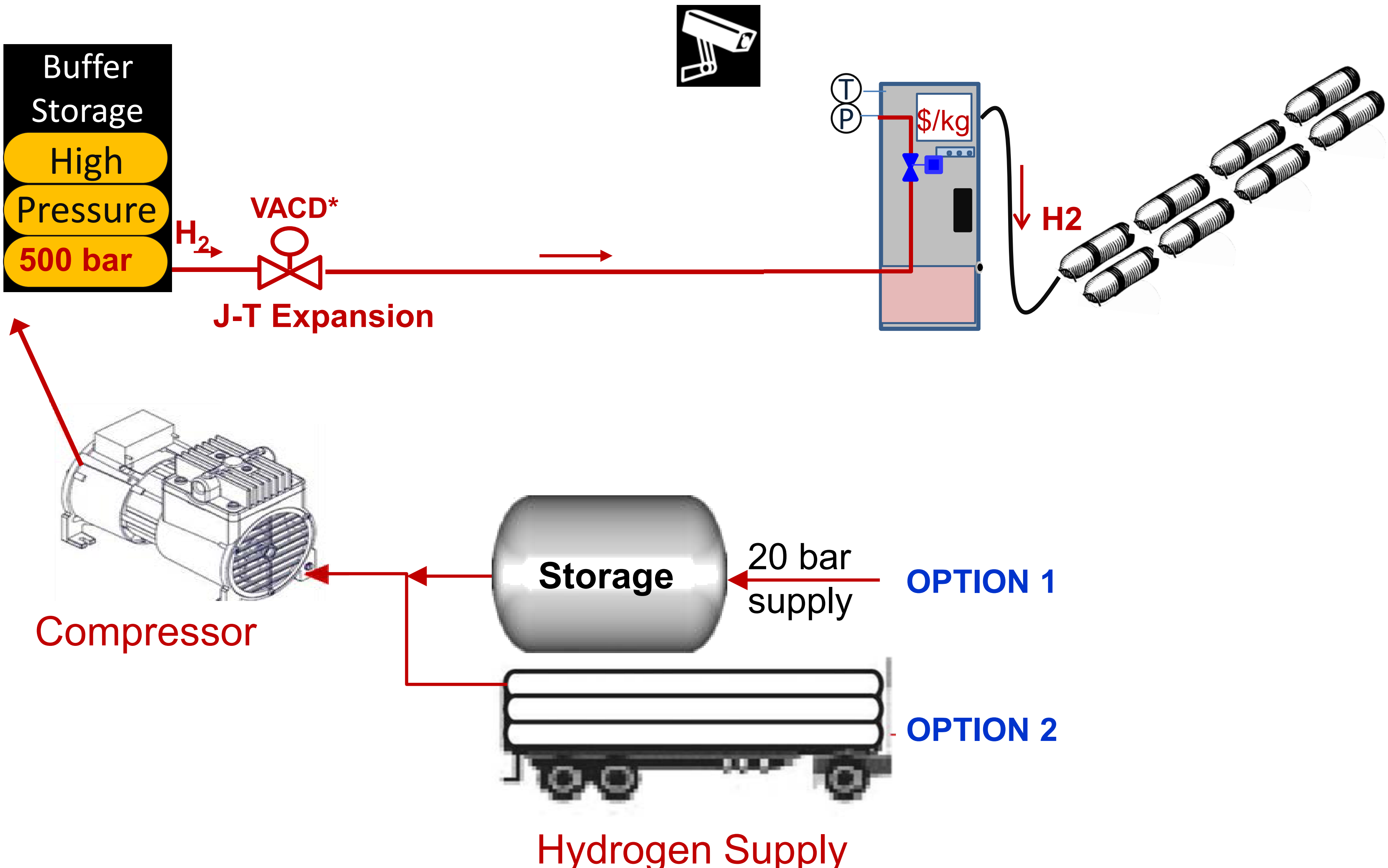
Assumed start-up year	2015
Construction Period (year)	1
Desired year dollars for cost estimates	2014
Real After-tax Discount Rate (%)	10.0%
Analysis period (years)	20
Debt Ratio (of total capital investment)	0%
Debt Interest (nominal)	6.0%
Debt Period	10

Hour of the day	Maximum # of HDV Fills Each Hour
1	0
2	0
3	2
4	2
5	2
6	2
7	2

Parameters to evaluate – Approach

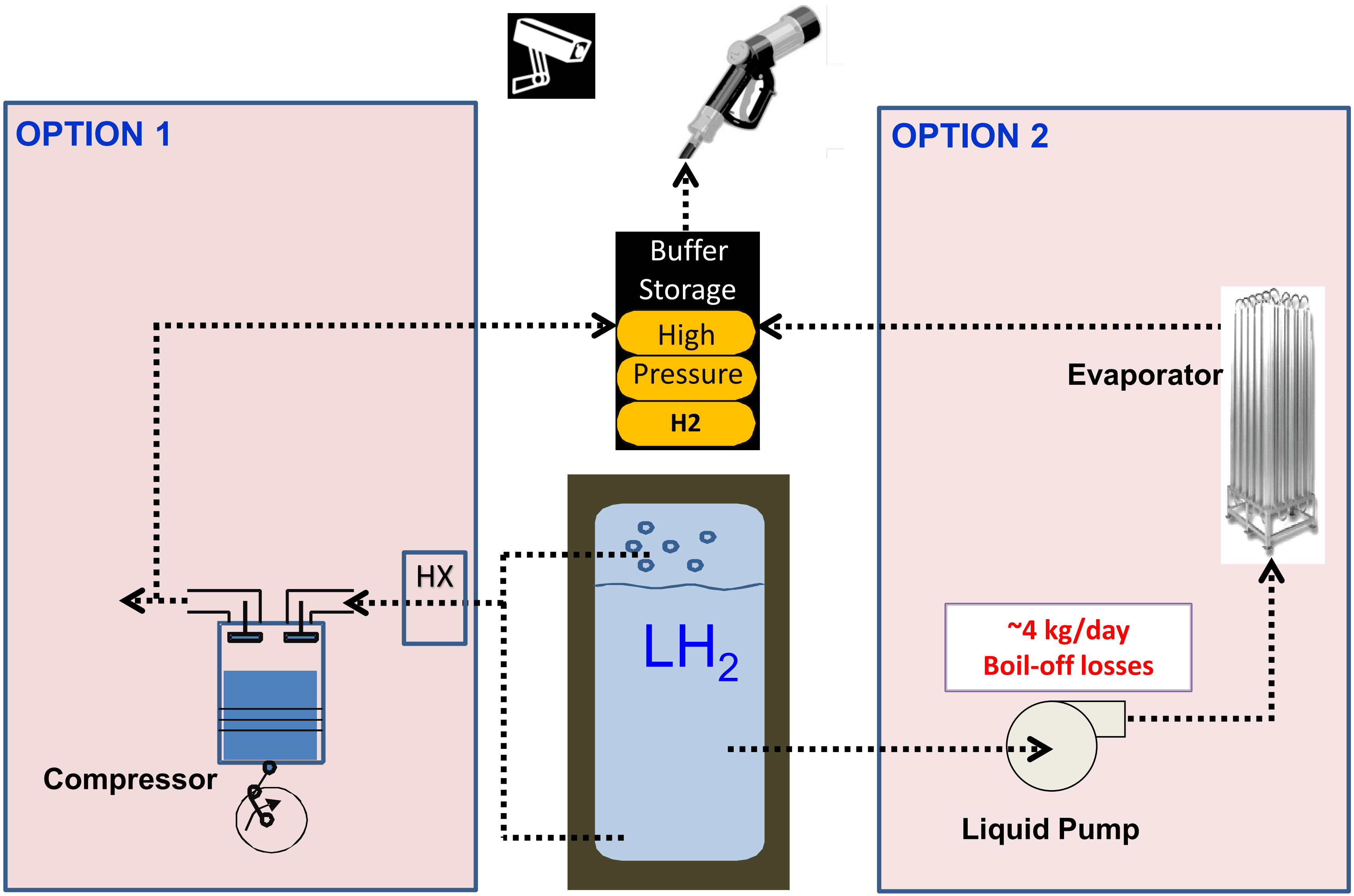
- Market parameters:
  - Fleet size (10, 30, 50, 100 buses)
  - Hydrogen supply (20 bar gaseous, liquid tanker, tube trailer)
  - Market penetration (production volume of refueling components, i.e., low, med, high)
- Technical parameters:
  - Refueling pressure (350 bar and 700 bar)
  - Tank type (III, IV)
  - 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)
  - Refueling configuration (e.g., compression vs. pumping)
  - SAE TIR specifies fueling process rates and limits (not a protocol)

Refueling configuration options for gaseous H_2 supply – *Approach*

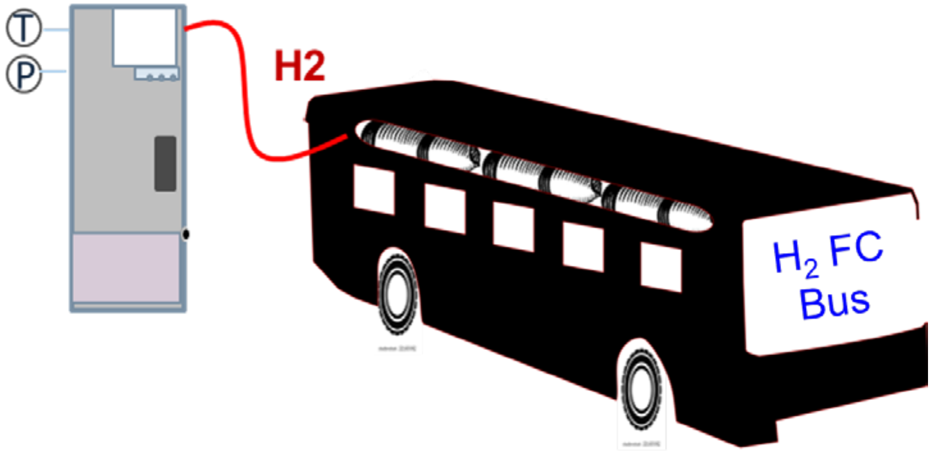


*variable area control device

Refueling configuration options with LH2 delivery – *Approach*



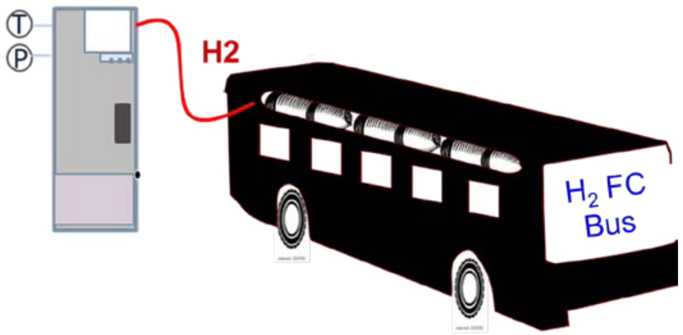
Evaluate precooling requirement for various vehicle tank types, fill pressures and refueling rates – Approach

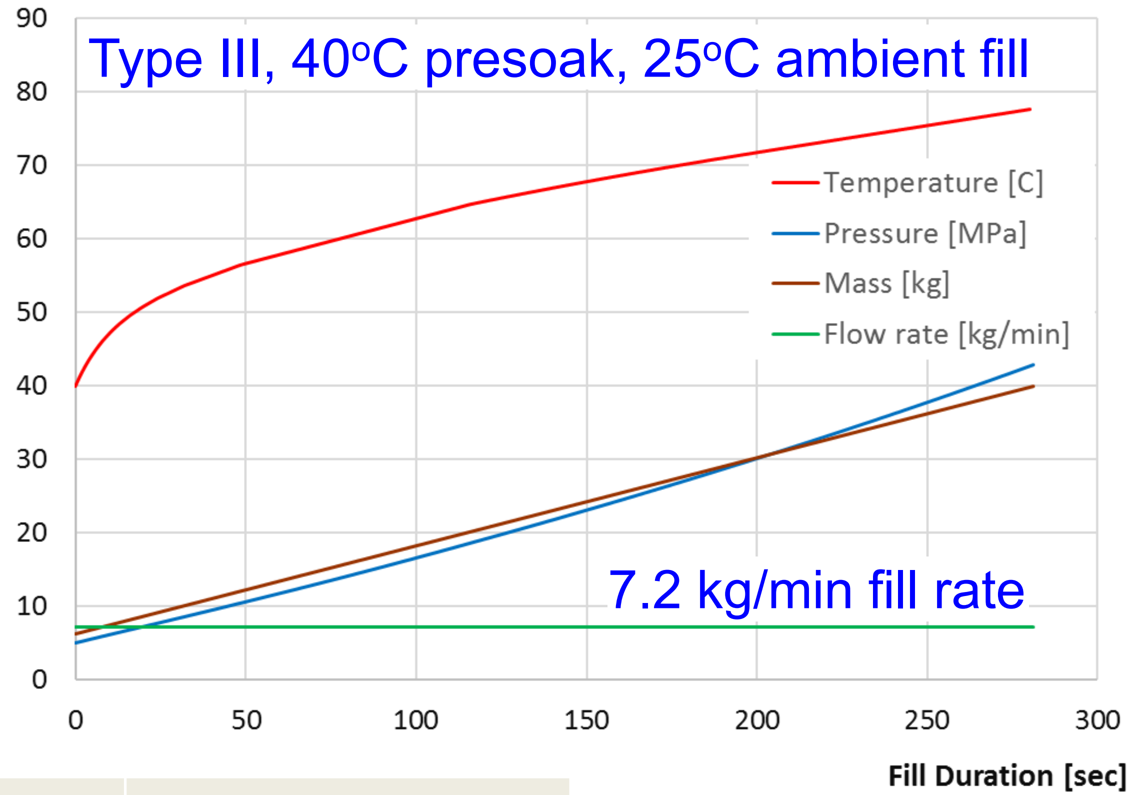


Bus Onboard Storage System	
Storage System Capacity [kg]	40
Number of Tanks	8
Tank Capacity [kg]	5
Initial tank pressure [MPa]	5
Geometry	
Outer Diameter [in]	17.74
Thickness [in]	1.78
Length [in]	88.7
Volume [L]	208

- Simulated tank fills with H2SCOPE Model
  - ✓ Type III and Type IV (350 bar)
- Simulated various refueling rates (1.8, 3.6, and 7.2 kg/min)
- Solved physical laws to track mass, temperature, and pressure
  - ✓ Determine precooling requirement

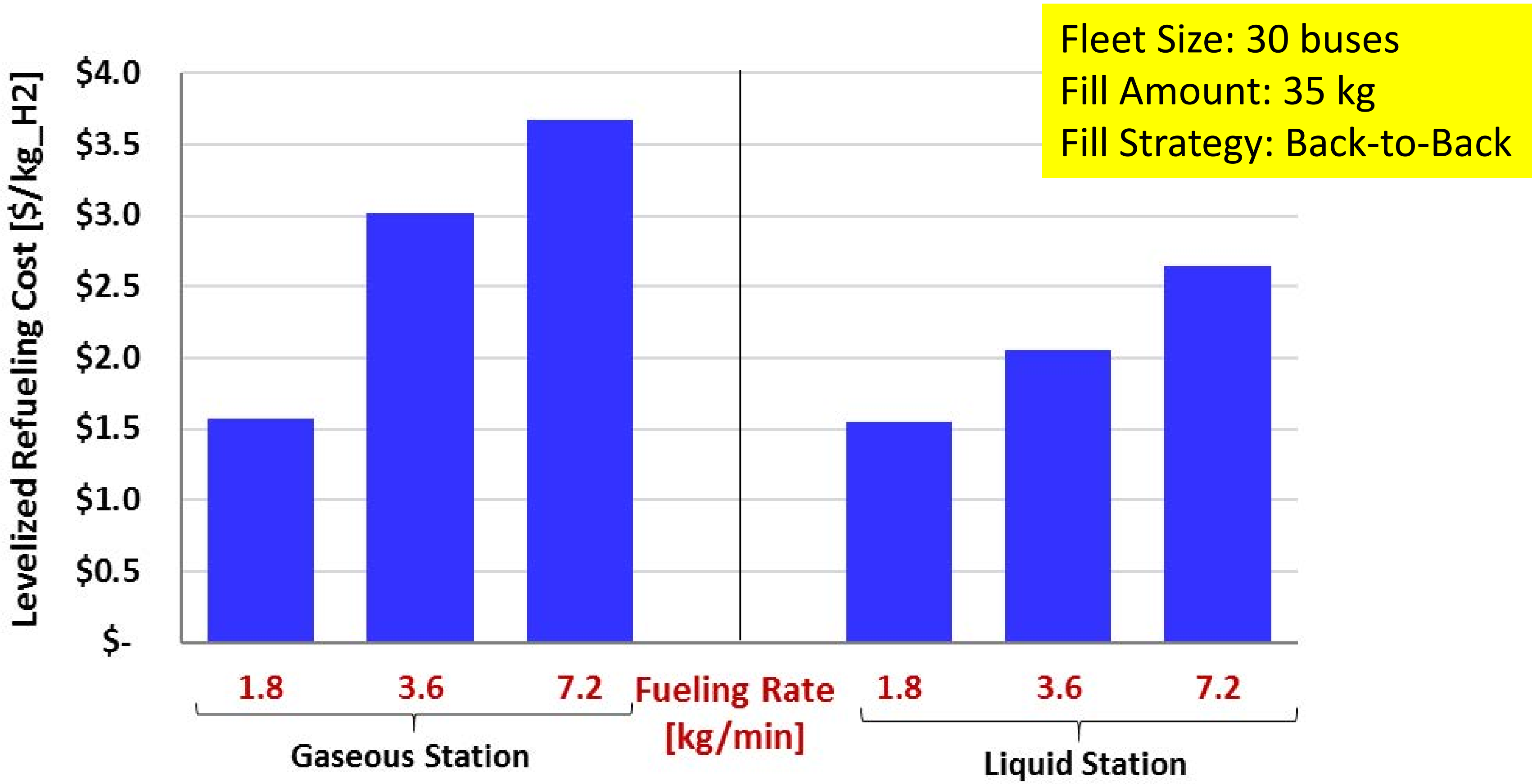
Type III tanks do not require precooling at all fill rates – *Accomplishment*





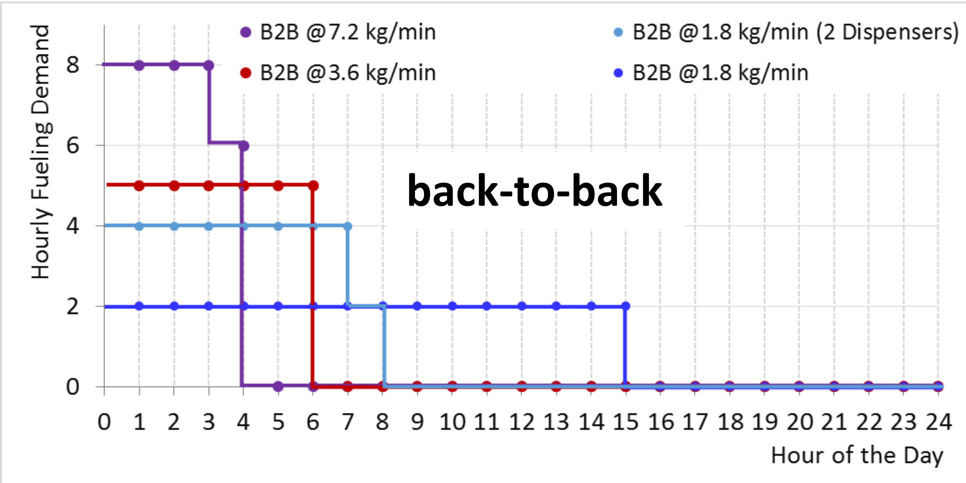
Tank Type	Fueling Rate [kg/min]	Required Precooling Temperature [°C]
III	1.8	No Precooling Required
	3.6	No Precooling Required
	7.2	No Precooling Required
IV	1.8	No Precooling Required
	3.6	18°C Precooling Required
	7.2	5°C Precooling Required

Impact of fueling rate on refueling cost –Accomplishment



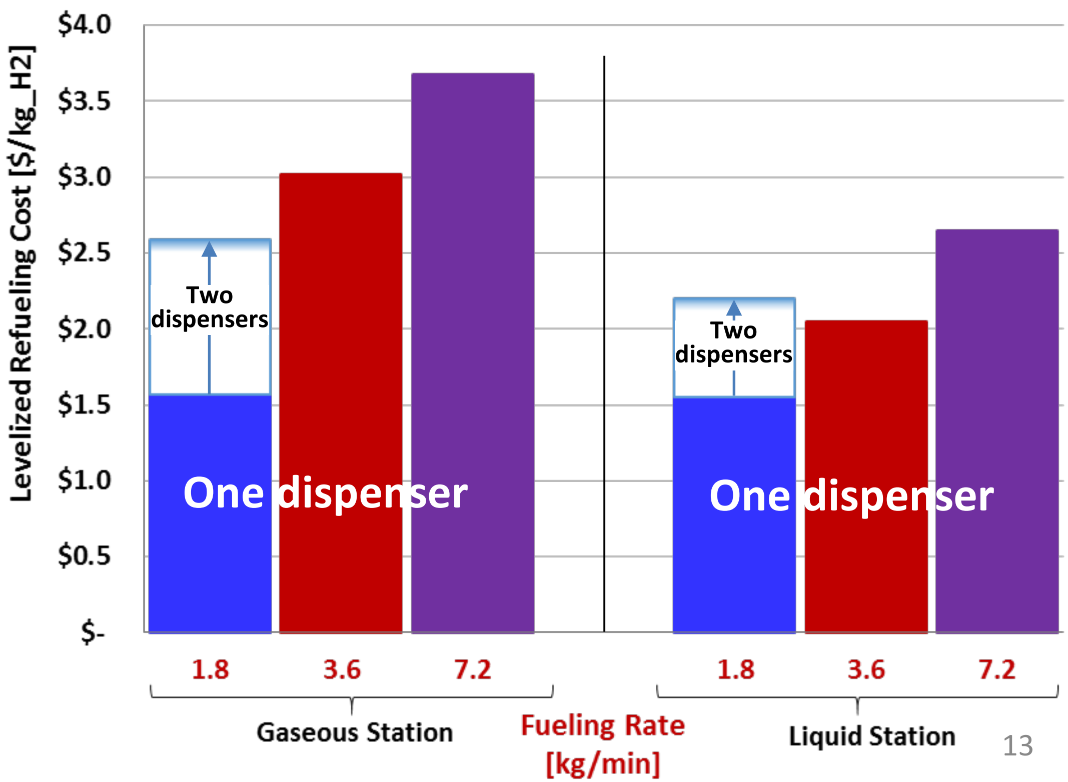
- Comparable cost for slow fills with gaseous and liquid stations
- Faster fills require higher capacity equipment and result in higher cost
- Liquid stations can handle faster fills with less cost increase

Impact of *fueling profile* on fueling cost –*Accomplishment*

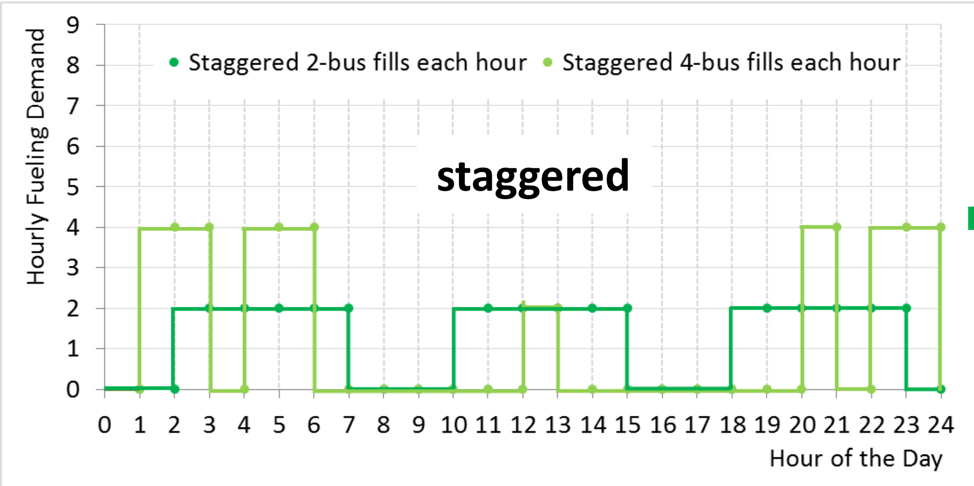


Fleet Size: 30 buses
Fill Amount: 35 kg

- Back-to-back fills increase fueling cost with higher fill rates
- To reduce fill time with slow fill (1.8 kg/min):
  - ✓ adding a dispenser is more favorable than doubling the fill rate for gaseous stations
  - ✓ doubling the fill rate is more favorable for liquid stations than adding a dispenser



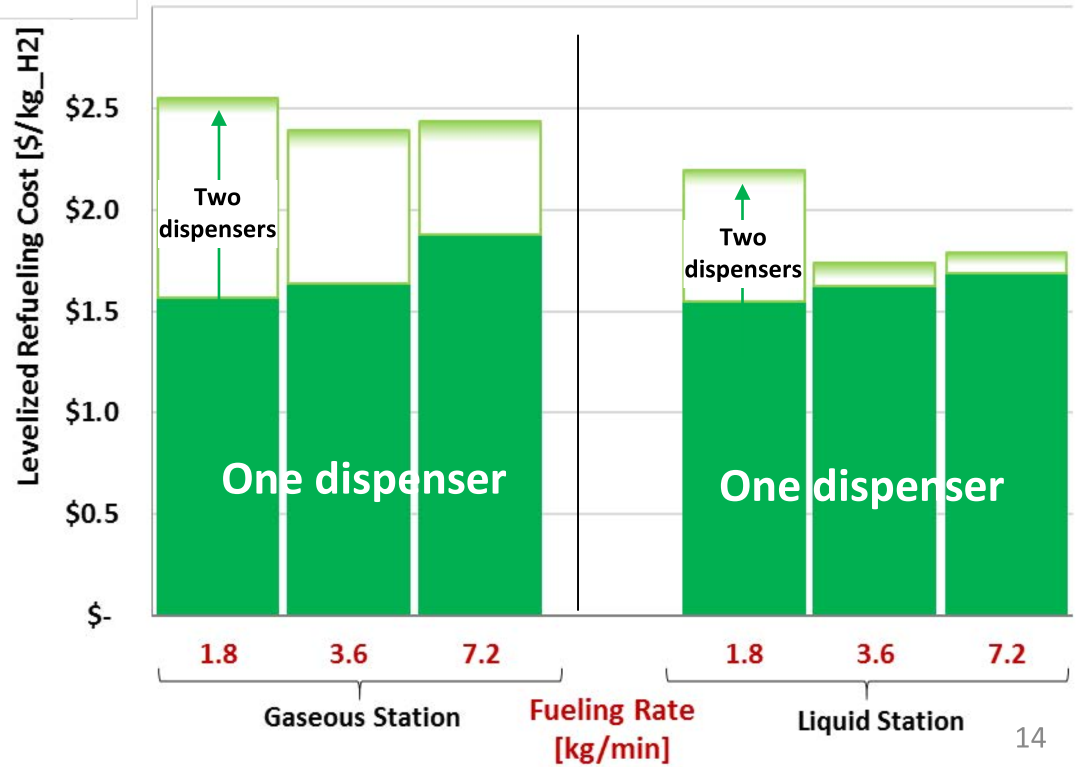
Staggered fueling can reduce fueling cost vs. back-to-back fills –Accomplishment



Fleet Size: 30 buses
Fill Amount: 35 kg

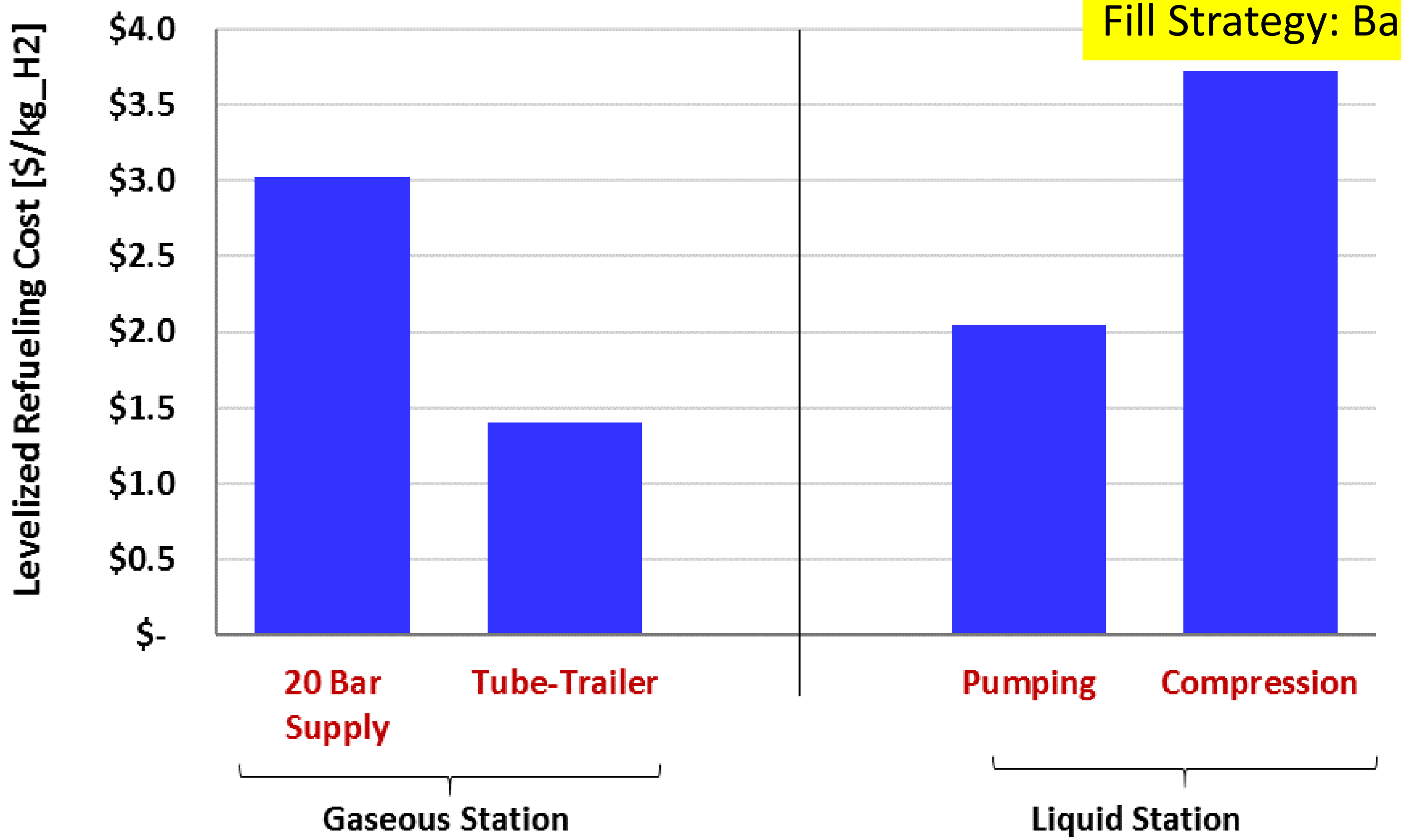
Staggered refueling may be restricted by bus availability for refueling

- Additional dispenser is required with the slow fill (1.8 kg/min) to satisfy hourly demand (4-bus fills).
- The additional dispenser increases the cost of refueling, favoring higher refueling rates with single dispenser.



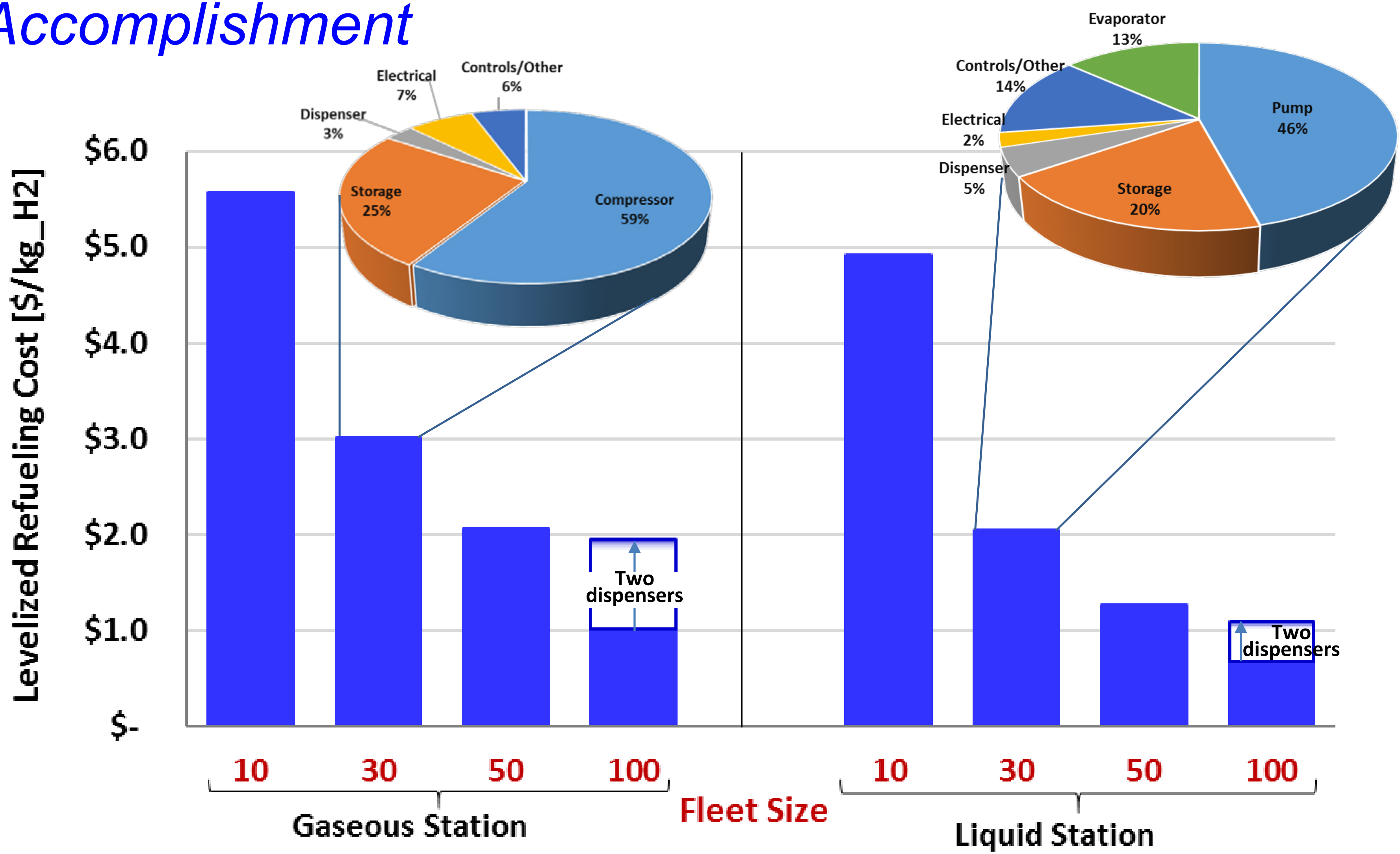
Impact of refueling station configuration on refueling cost –Accomplishment

Fleet Size: 30 buses
Fill Amount: 35 kg
Fill Rate: 3.6 kg/min
Fill Strategy: Back-to-Back



- Tube-trailer hydrogen supply minimizes station cost for moderate-sized fleets
- Tube-trailer shifts cost upstream of station and has limited payload
- For liquid station, pumping provides a lower cost option

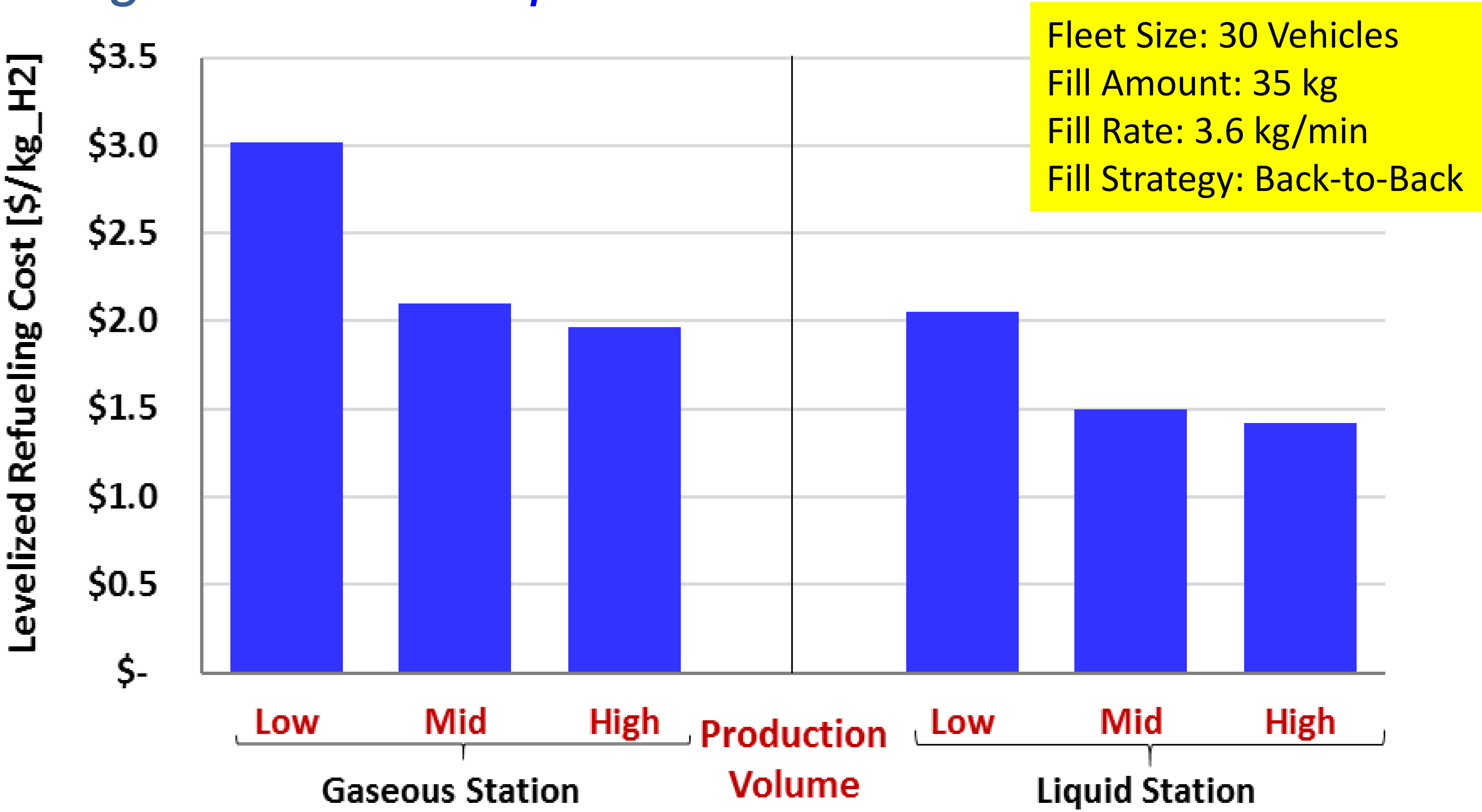
*Impact of **fleet size** (demand) on refueling cost – Accomplishment*



- ➢ Strong economies of scale with fleet size (daily demand)
  - ✓ fueling cost can drop to ~$1/kg_{H2}$ with large fleet size
- ➢ Liquid station, in general, provides a lower cost option
- ➢ Compression and pumping dominate fueling cost

Fill Amount: 35 kg
Fill Rate: 3.6 kg/min
Fill Strategy: Back-to-Back

Impact of station equipment production volume on refueling cost – Accomplishment



- ➢ Refueling cost can be reduced to $1.5/kg$_{H2}$ with high production volume of fueling components (with learning)

Summary – Progress and Accomplishment

- Lower cost for refueling HDV fleet compared to refueling LDVs
- Strong economies of scale can be realized with fleet size and fill amount (impacting station demand/capacity)
- Faster fills require higher capacity equipment and result in higher fueling cost
- The cost impact of faster fills is lower for LH_2 stations than GH_2 stations
- Liquid station, in general, provides a lower cost option for HDV fleet refueling compared to gaseous stations
  - ✓ comparable cost for slow fills with gaseous and liquid stations
- Back-to-back fills increase fueling cost with higher fill rates, while staggered fueling reduces fueling cost, even at higher fill rates
- Compression and pumping dominate fueling cost
- Tube-trailer may be beneficial for small fleets in early markets
  - ✓ shifts cost upstream of station and has limited payload
- Refueling cost can be reduced to \$1-\$1.5/kg_{H2} for large fleets and high production volume of fueling components

Future work

- Examine precooling requirement and cost for:
  - Type IV tank fueling with various fill rates, amount and strategies
  - 700 bar tanks
  - ✓ Cost of precooling can be significant, especially with back-to-back fills
- Evaluate the impact of typical bus service schedules on cost
- Add refueling profiles for commercial (non-fleet) HDV fueling stations
  - ✓ Including station capacity utilization in early markets
- Evaluate the impact of LH_2 boiloff losses with various fueling strategies (back-to-back vs. staggered fills)
- Peer-review model and post in public domain

Collaborations and Acknowledgments

Collaborators and Partners:

– Daryl Brown, Energy Technology Analysis LLC: provided updated refueling components cost estimates; and conducted model reviews

– Fuel Science, George Parks: conduct model reviews

– Boyd H2, Bob Boyd: provided information on configuration of current refueling stations and conducted model reviews

Project Summary

- **Relevance:** Model near-term refueling stations for heavy duty fuel cell vehicle fleets. Evaluate impact of design, operation and economic parameters of various hydrogen fleet refueling station configurations on the fueling cost. Identify cost drivers of current technologies for hydrogen refueling. Assist FCTO with setting cost and performance targets in MYRD&D planning.
- **Approach:** Collaborate to acquire/review model inputs and examine/review model and results. Acquire current cost of refueling and delivery components from vendors and industry experts. Develop modeling structure to evaluate the impact of key market, design, and economic parameters on hydrogen fueling cost. Evaluate performance of various hydrogen supply options and station design configurations. Identify major cost drivers for hydrogen refueling. Review modeling approach and results with partners, Tech Teams, and experts from industry.
- **Collaborations**: Collaborated with researchers from other national labs and interacted with experts from the industry with knowledge and experience on hydrogen refueling operation and strategies that are relevant to this project. Acquired information needed for modeling and simulations and received valuable input to complete the project.
- **Technical accomplishments and progress:**
  - Developed a modeling framework to examine near-term refueling cost for hydrogen heavy duty fleets
  - Strong economies of scale can be realized with fleet size and fill amount (impacting station demand/capacity)
  - Faster fills require higher capacity equipment and result in higher fueling cost
    - The cost impact of faster fills is lower for LH_2 stations than GH_2 stations
  - Liquid station, in general, provides a lower cost option for HDV fleet refueling compared to gaseous stations
  - Back-to-back fills increase fueling cost with higher fill rates, while staggered fueling reduces fueling cost, even at higher fill rates
  - Refueling cost can be reduced to $1-$1.5/kgH2 for large fleets and high production volume of fueling components
- **Future Research**: Examine precooling requirement and cost for Type IV tank fueling with various fill rates and strategies. Acquire samples of bus fleet activity schedules to implement in the model and evaluate their impact of fueling strategy on cost. Examine refueling profiles for commercial HDV fueling stations, including station capacity utilization in early markets.

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Project PD14

Argonne NATIONAL LABORATORY

Acronyms

- ANL: Argonne National Laboratory
- CARB: California Air Resource Board
- CEC: California Energy Commissions
- DOE: Department of Energy
- FC: Fuel Cell
- FCTO: Fuel Cell Technologies Office
- FY: Fiscal Year
- GH_2: gaseous hydrogen
- H_2: Hydrogen
- H2SCOPE: Hydrogen Station Cost Optimization and Performance Evaluation
- HDV: Heavy Duty Vehicle
- J-T: Joule Thompson
- LDV: Light Duty Vehicle
- LH_2: Liquid Hydrogen
- MHDV: Medium- and Heavy-Duty Vehicles
- MYRD&D: Multi-Year Research, Development, and Demonstration
- NOx: Nitrogen Oxides
- PM: Particulate Matter
- SAE: Society of Automotive Engineers
- TIR: Technical Information Report
- VACD: Variable Area Control Device
- ZEV: Zero Electric Vehicle

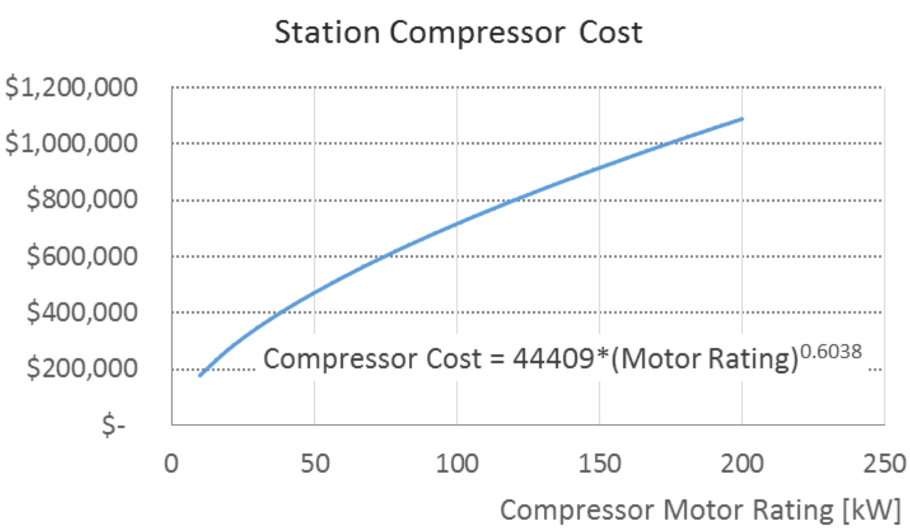
Backup Slides

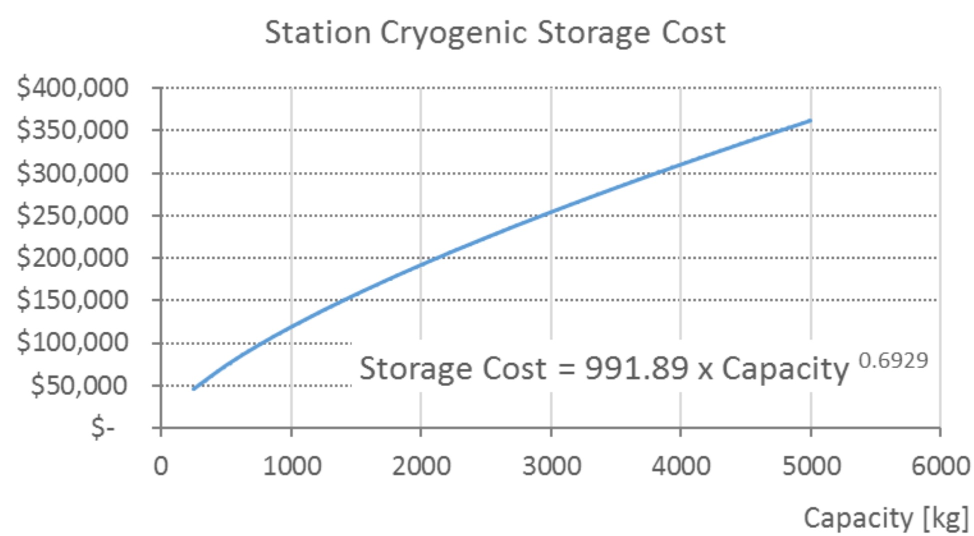
Developed components cost and economic assumptions – Accomplishment

- Cryogenic Pump: 350 bar@2 kg/min, $425000
- Gaseous Storage:
  - ✓ Medium Pressure Gaseous: $1200/kg
  - ✓ Low Pressure Gaseous: $1000/kg
- Dispenser: $100,000

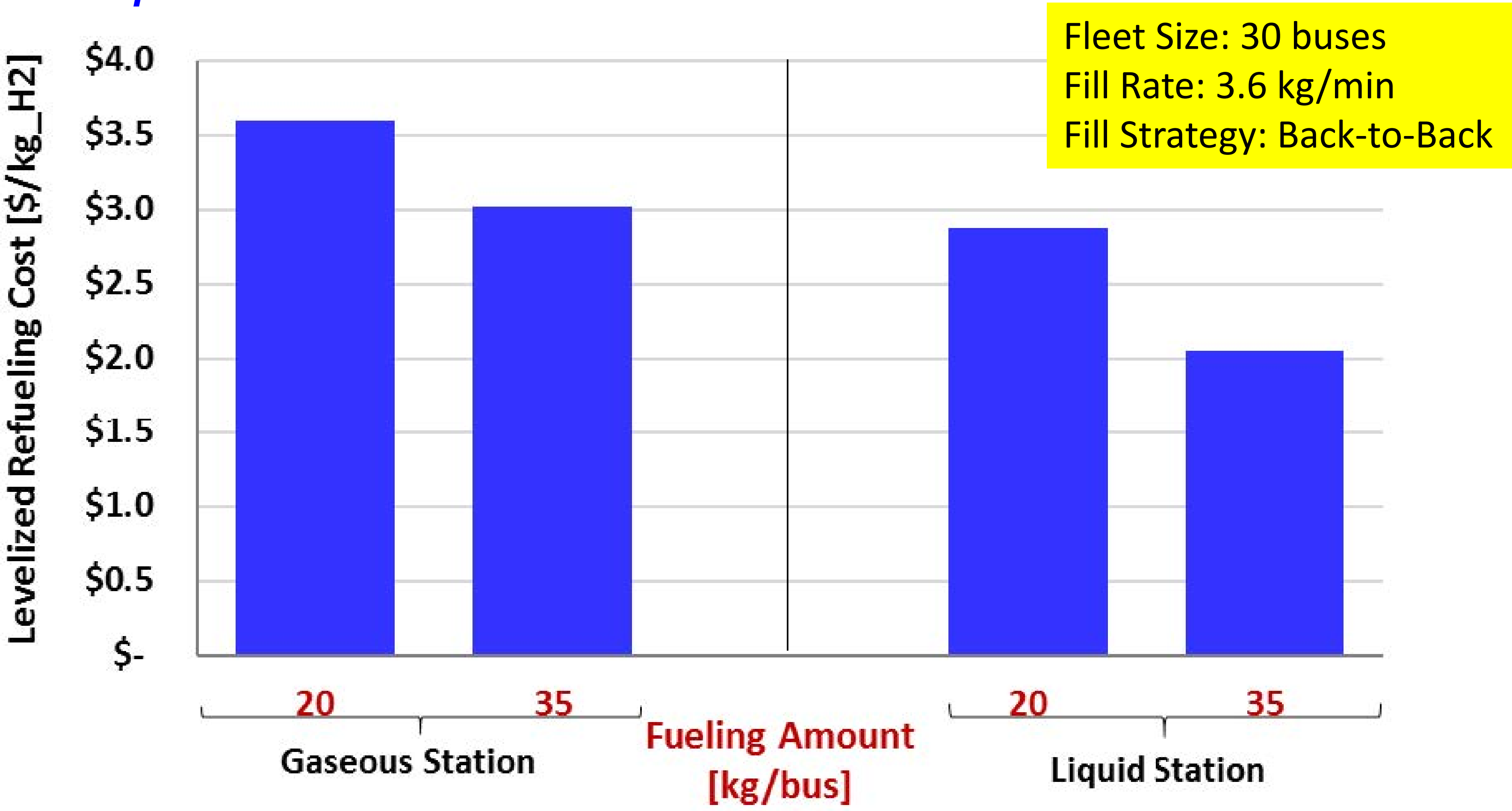
General Economic Assumptions

Assumed start-up year	2015
Construction Period (year)	1
Desired year dollars for cost estimates	2015
Real After-tax Discount Rate (%)	10.0%
Project period (years)	20





Impact of fueling amount (per bus) on refueling cost – Accomplishment



- Cost reduction with increased dispensed amount
- Liquid station, in general, provides a lower cost option