



Hydrogen Fueling Infrastructure Research and Station Technology

Consolidation

Danny Terlip*
Amgad Elgowainy
Krishna Reddi
Kareem Afzal

National Renewable Energy Lab
Argonne National Lab
Argonne National Lab
PDC Machines Inc

**Presenter*

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Project ID# PD133

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Timeline and Budget

Project start date	Oct 2015
FY16 DOE funding	\$ 500k NREL \$ 200k ANL
FY17 planned DOE funding	\$ 674k NREL \$ 160k ANL
Total DOE funds received to date	\$ 1.674M NREL \$ 360k ANL
Total Project Budget	\$ 2.034M
Project Timeline	Oct '15 – Sep '17

Barriers

Technology Validation (D) – Lack of Hydrogen Refueling Infrastructure Performance and Availability Data

Delivery (E) – Gaseous Hydrogen Storage and Tube Trailer Delivery Costs

Partners

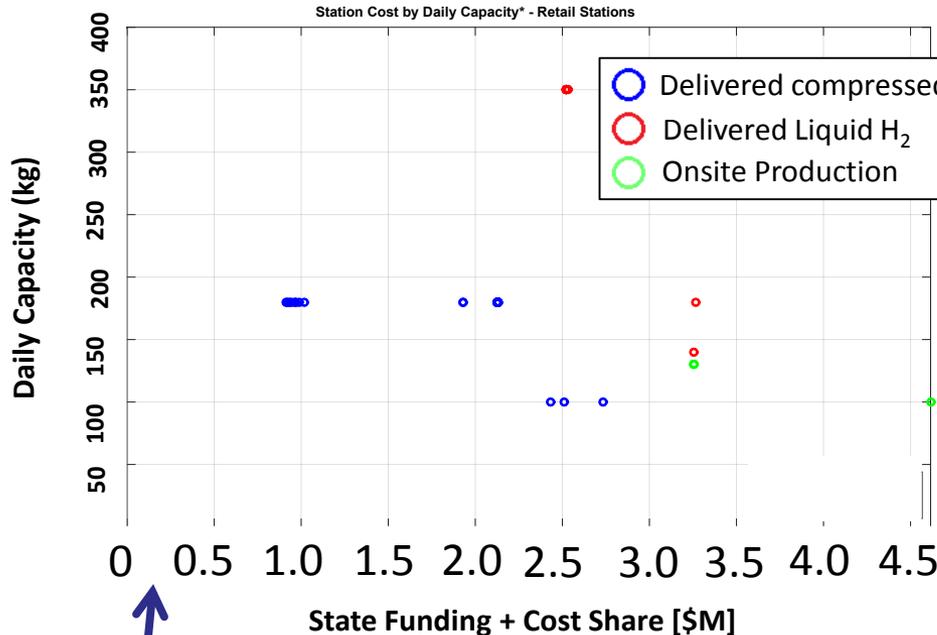
- Argonne National Lab
- PDC Machines
- National Renewable Energy Lab (Project lead)

Problem Statement

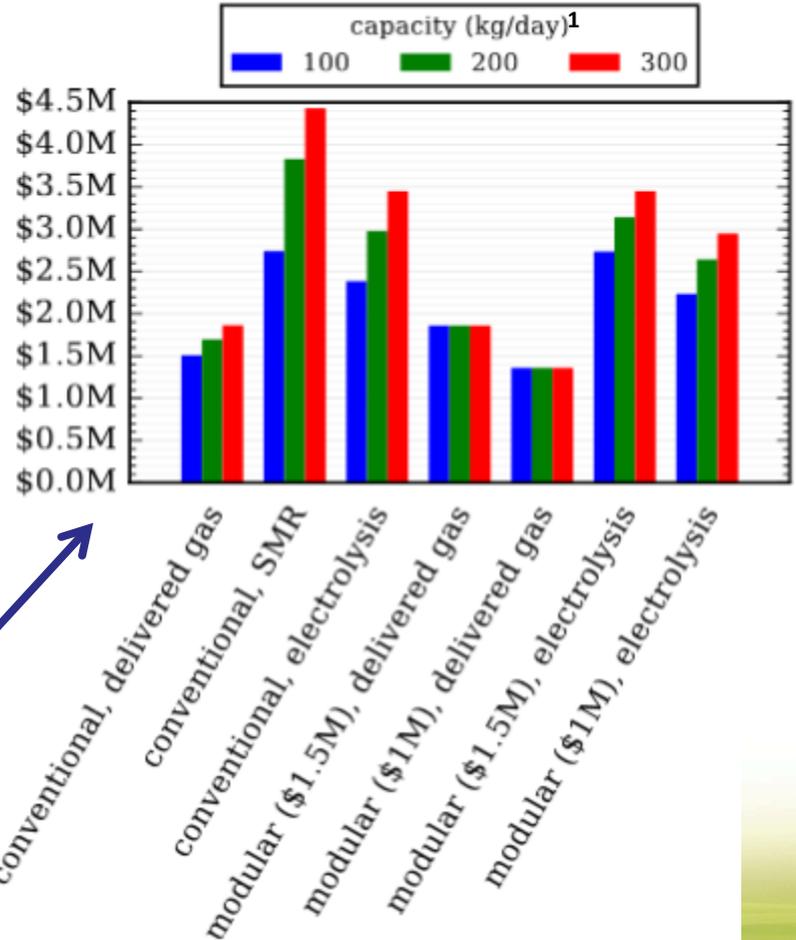


Hydrogen station capital costs are too expensive

Hydrogen cost to break even in 7 years requires selling hydrogen at > \$14/kg¹



*Based on budget data from station awards
<http://www.nrel.gov/hydrogen/images/cdp-retail-infr-40.jpg>



Real Station Construction Budget Data

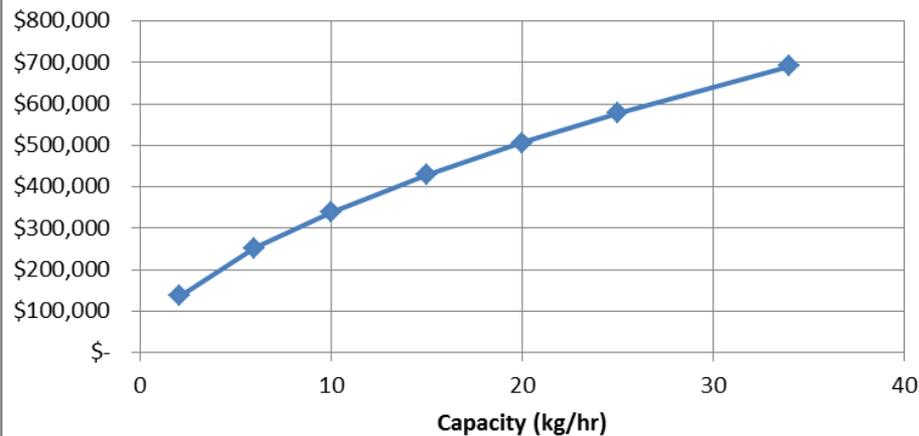
Analysis Data



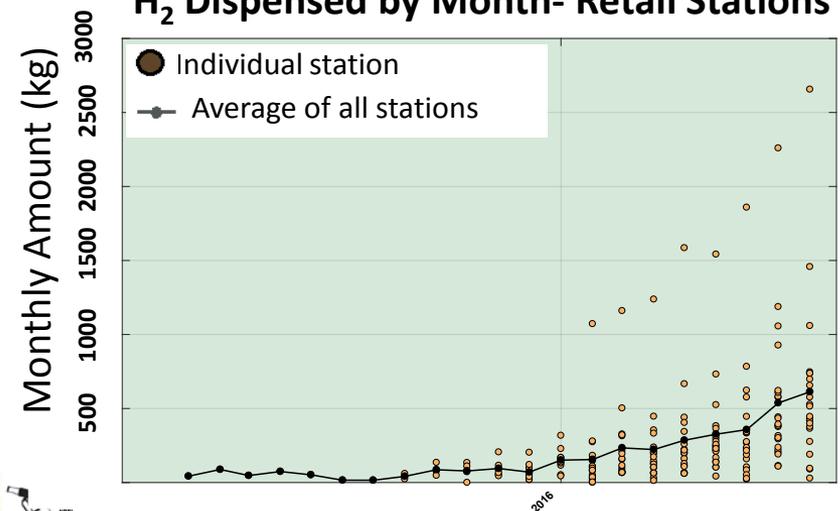
Compressors make up a large portion of capital costs which only increase with throughput

Field data show station throughput is strongly increasing

Uninstalled Capital Cost 900b Compressors (2016)



H₂ Dispensed by Month- Retail Stations

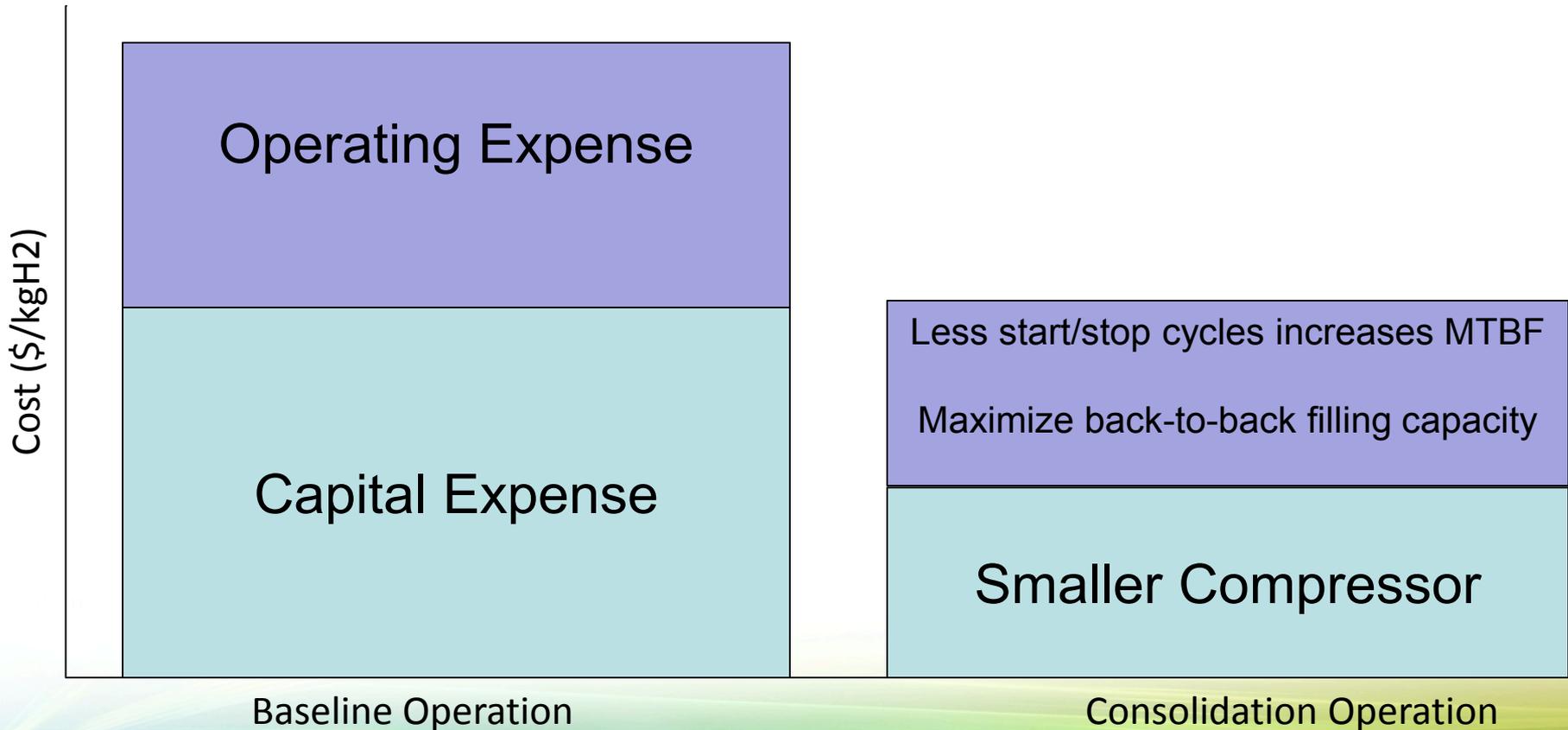


<http://www.nrel.gov/hydrogen/images/cdp-retail-infr-19.jpg>

Reducing Capital Costs



ANL Consolidation Algorithm projected to reduce the compression contribution to hydrogen cost (in terms of \$/kgH₂) by approximately 50%



Approach – Design and build a station to validate Consolidation algorithm



- **ANL Tube-Trailer Consolidation Concept**

- Efficient utilization of the tube-trailer payload and compressor operation

- Compress low pressure hydrogen into high pressure storage tubes during low- or no-demand

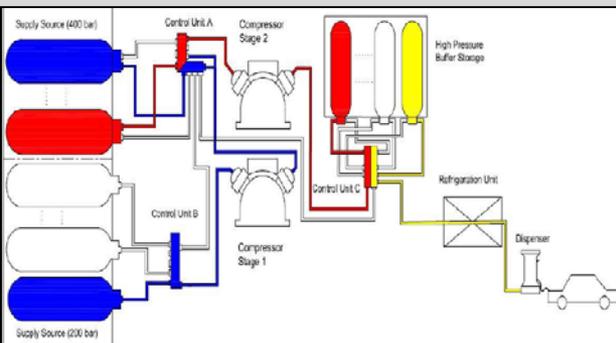
- Compressor can use high-pressure storage tubes as suction during high demand, such that it operates as high as 10 times its rated throughput

- Reduce compressor size required dramatically

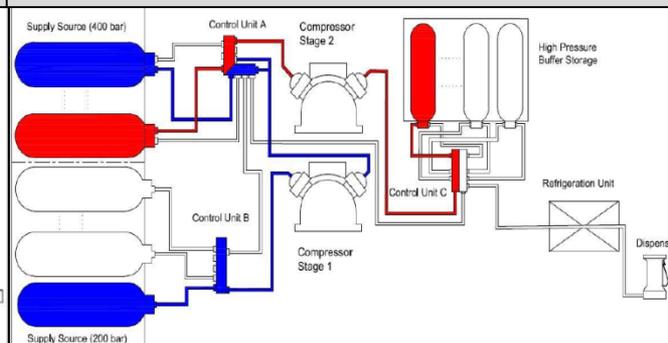
- Reduce capital expenditure at stations by up to 40%¹

Consolidation algorithm defined to lower capital costs at hydrogen stations

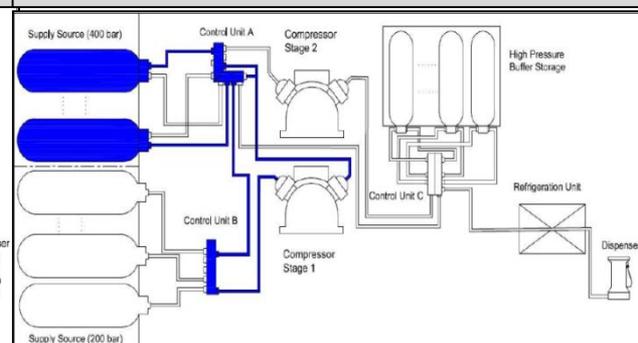
Compress MP/HP tanks while filling from HP



Compress MP/HP tanks when not filling



Consolidate MP tanks when LP empty



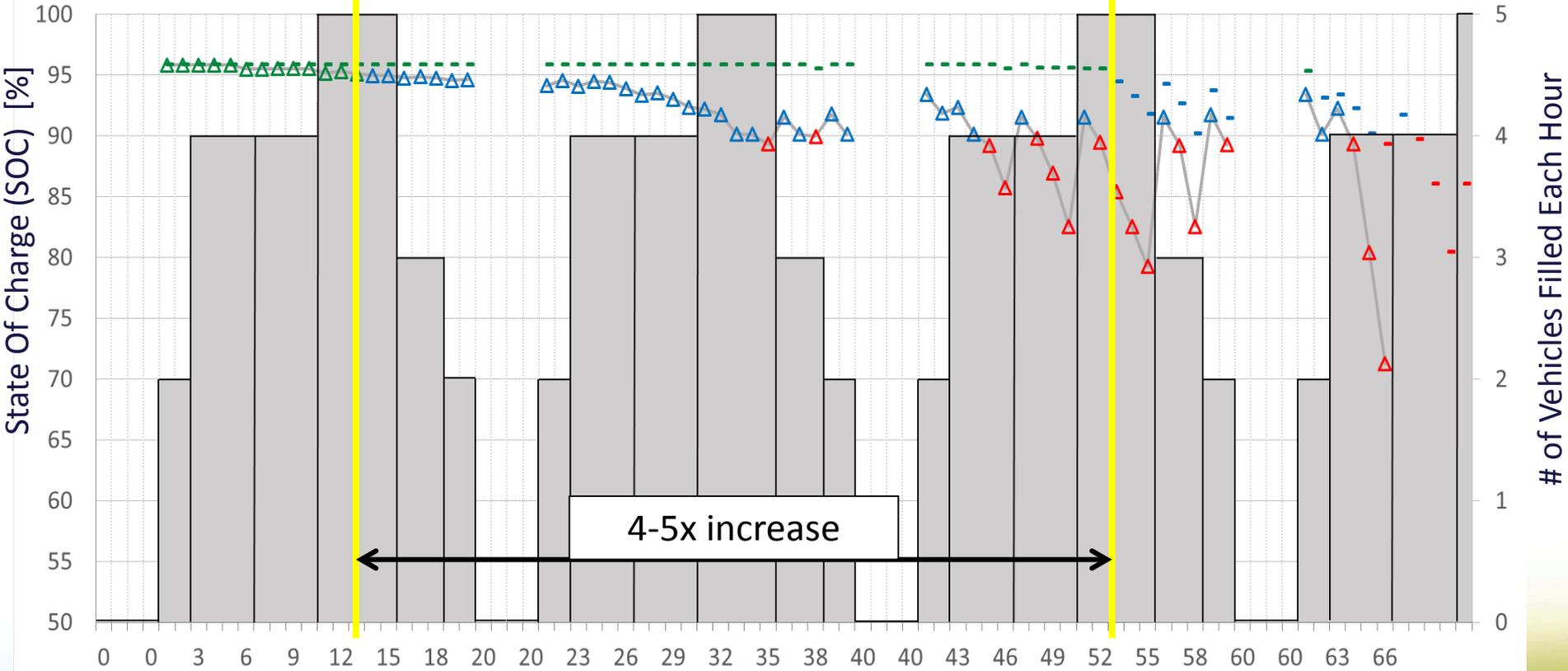
Approach - Simulated Consolidation Algorithm



Simulation of station shows that consolidation enables 4-5x increase in number of complete vehicle fills possible

▲ Baseline operation
 ■ Consolidation operation

Green → 95% < SOC (i.e., Full Charge)
 Blue → 95% > SOC > 90%
 Red → 90% > SOC



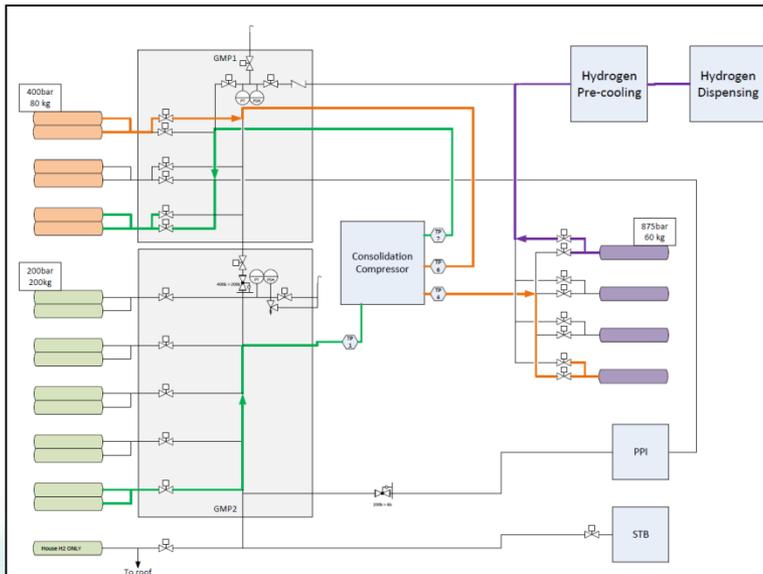
Fill operation with 3.7 kg fills and 2-bank buffer storage (1-hose)

Total # of Refueled Vehicles

Approach – Design and build a station to validate Consolidation algorithm



- **PDC Machines Novel Compressor Design**
 - Two-stage diaphragm compressor
 - Inter-stage flow allowing single stage compression
 - Developing control algorithm and capability through this project
- **Hydrogen Infrastructure Testing and Research Facility (HITRF)**
 - Simultaneous bi-direction flow of storage tanks at three pressure levels
 - Centralized visual system SCADA
 - Data logging for station pressures, temperature, power, energy, etc.
 - SAE J2601 T40 back to back filling capability (goal of 5, 4 kg fills)



Approach – Three phase plan to accomplish testing



- **Phase I – Setup [Oct. 2015 – Jan. 2016]**

- Design of hardware and controls
- Major equipment order
- Operation simulations/optimization with actual performance specifications

Project Goal: *Long-lead items successfully sourced*

COMPLETE

- **Phase II – Preparation [Feb. 2016 – May 2017]**

- Station, compressor and vehicle simulator build
- Algorithm development and testing

Project Goal: *System design will adequately meet the intent of the project*

IN PROGRESS

- **Phase III – Development [Jun. 2017 – Sep. 2017]**

- System operation and optimization
- Summary analysis and reporting

Project Goal: Issue report to DOE on testing results

FUTURE

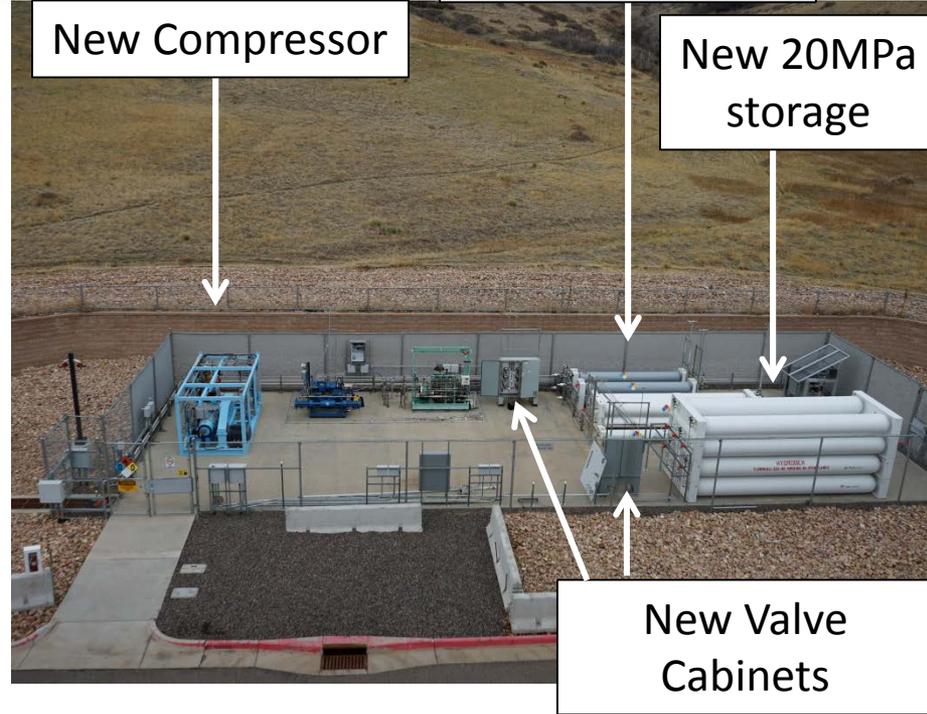
Accomplishments – Build out completed



HITRF 2014



HITRF 2017



New 90MPa storage

New Compressor

New 20MPa storage

New Valve Cabinets

Eight new major station components have been added to the HITRF to support Consolidation Testing

New Chiller

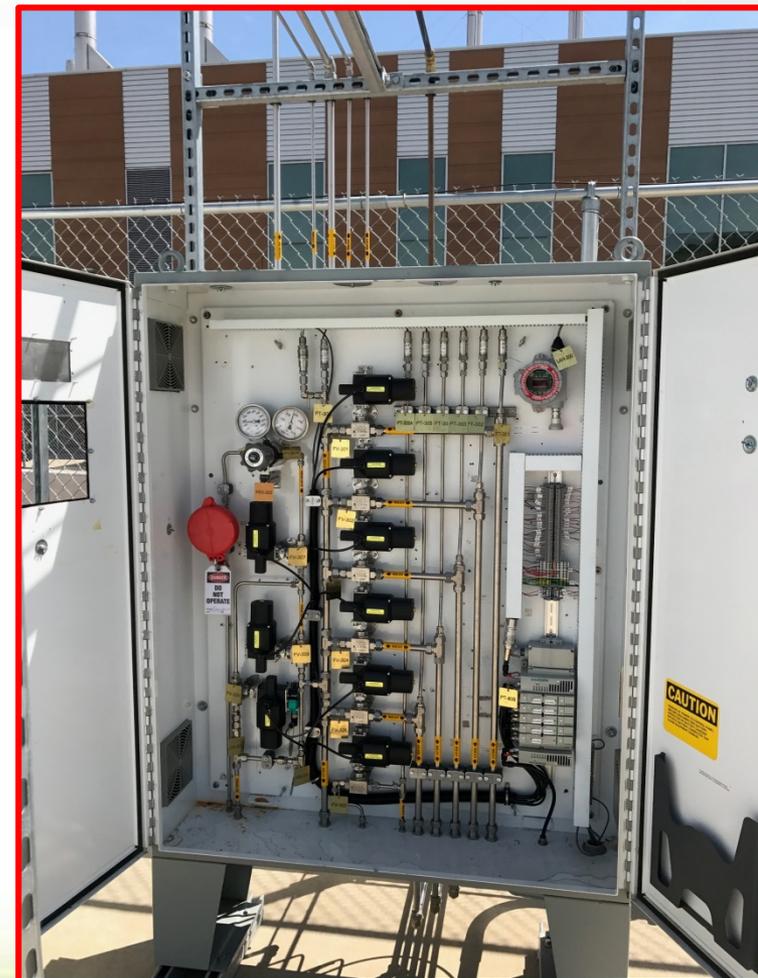
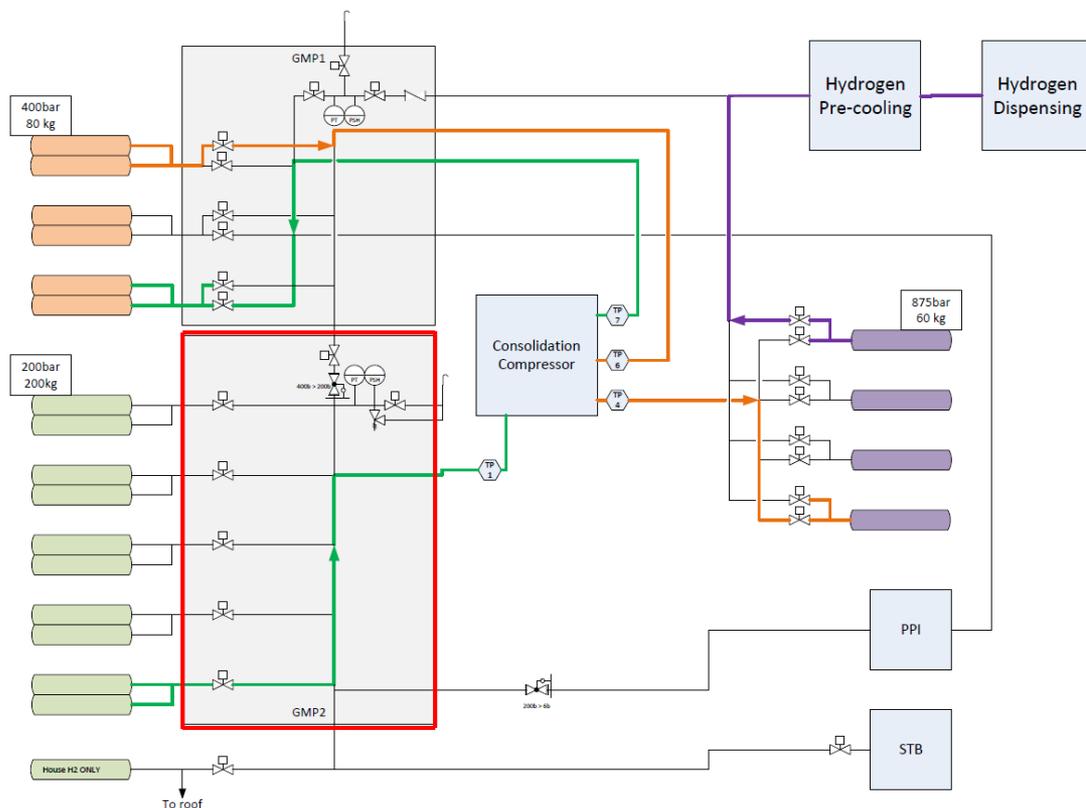
New Heat Exchanger



Progress – Low Pressure Gas Management Panel Design and Construction



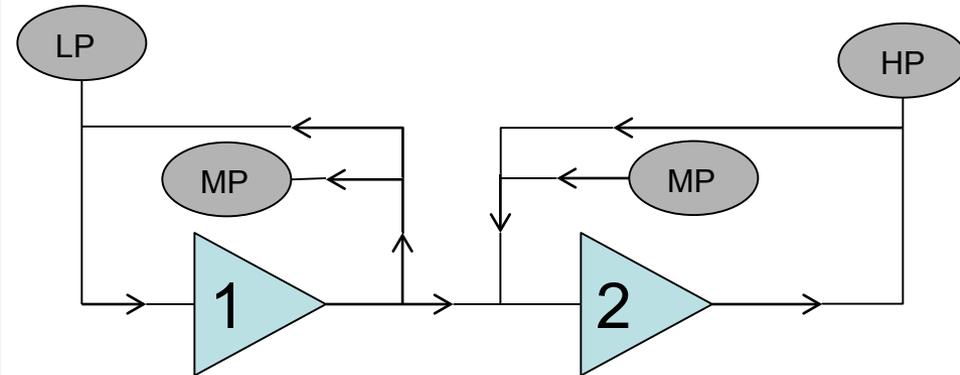
Valve and instrumentation upgrades necessary for low pressure storage tank additions completed



Progress – Compressor construction and delivery complete. Commissioning underway



- 2 stage compressor that can be used in multi mode operation
- Maximize input pressures, which maximizes throughput and allows for downsizing the compressor



PDC Machines has developed a compressor package capable of implementing the Consolidation Algorithm. Testing at NREL will enable optimization of the algorithm

Responses to Previous Year Reviewers' Comments



- The presentation did not make clear how this novel compressor design was an advantage over two compressors achieving the same objective. A more practical approach would be to move the proposed “first stage” of the novel compressor to the terminal compression location and using 400–450 bar tube trailers to deliver hydrogen. This concept is currently being developed by some gas merchants. This achieves the same objective as this project without the need to develop this technology for the station itself.
- *"The consolidation method allows the station compressor to delivery high throughput during peak refueling demand hours by supplying it with high pressure stream from the tubes that were consolidated to this high pressure during off-peak hours. The alternative method of delivering high pressure hydrogen gas in a tube-trailer to the station will provide similar throughput only when the tubes are near their maximum pressure, but the throughput will decrease with time as the pressure in the tubes drops as a result of payload consumption with each vehicle fill. This is why consolidating the tubes during off-peak hours can restore the high pressure supply to the compressor, thus improving refueling capacity during peak demand hours (with improved utilization of the station compressor)."*

Collaborations



Strong national lab and industry collaboration

- **Argonne National Laboratory**

- Partner DOE lab
- Design and simulation of the consolidation concept and algorithm
- Station build support
- Results and optimization analysis

- **PDC Machines**

- Subcontractor to NREL
- Leading industry member in hydrogen compressors
- Compressor design and build
- System optimization



Remaining Challenges and Barriers



Preliminary test data expected in May

- Commission Compressor
 - Compressor delivered to NREL and placed at HITRF
 - PDC on site to commission April 2017
 - Concern with speed of valve changes at high flow rates
- Commission New Chiller and Heat Exchanger
 - Chiller and heat exchanger delivered to NREL and placed at HITRF
 - Electrical changes required
 - Triple block heat exchanger sited

- Perform Baseline and Consolidation Tests
 - Capture station performance using all new components
 - Implement consolidation algorithm on compressor and optimize
 - Metrics to define success
 - Number of vehicle fills possible
 - SOC of vehicles after fills completed
 - Station storage pressures
 - Compressor energy consumption

- Vehicle Simulator

- Ability to test station performance without vehicle OEM involvement
- Significant interest from hydrogen station and vehicle industry
- Self contained system than can be transported
- Ability to fill and vent simultaneously to simulate back-to-back filling



- Modeling, Simulation and Development of Consolidation Concept
 - Simulated various refueling configurations for baseline and consolidation operation
 - Identified size of buffer storage and fill amount as key factors impacting station fueling capacity/performance
 - Determined that consolidation operation can extend capacity of station for full vehicle fills, with back-to-back capability, by a factor of 400-500%
- Station Upgrades
 - 90MPa and 20 MPa Storage upgrades completed Fall 2016
 - Compressor delivered March 2017 and commissioned April 2017
 - Pre-cooling system commissioned April 2017
- Testing is scheduled to begin April 2017
 - Optimization of consolidation algorithm will follow

Technical Back-Up Slides

Approach – Unique Hardware



Vehicle Simulator Major System Components				HITRF Major System Components			
Storage Tanks	875b 36L each	15 tanks	Type 4 storage	Low Pressure Storage	200 b, 189 kg	5 banks	Type 1 ground
IRDA Communication	Receptacle Mounted	CSA HGV 4.3 SAE J2799 compliant		Med Pressure Storage	400b, 103 kg	3 banks	Type 1 ground
Back-to-back capability	3 tanks per fill line	Fill and vent simultaneously		High Pressure Storage	875b, 62 kg	4 banks	Type 2 ground
User Interface	PLC touch screen	Automated safety features		Pre-cooling	16HP	Triple block	aluminum block
Utility	80 psi air or nitrogen	120V	NEC Class 1 Div 2	Dispenser	350b, 700b	Separate hoses	SAE J2601- 2014 T40

Key Simulation Parameters- Relevance



- Pressure limits/ constraints

Process Limits	Max	Min	MAWP
High Pressure Cascade Pressure [MPa]	91	42	93
40 MPa Storage Pressure [MPa]	44	5	45.9
20 MPa Storage Pressure [MPa]	26	2	27.5
1st Stage Independent Suction (2 to 40 MPa)	20	2	N/A
2nd Stage Independent Suction (13 to 95 MPa)	40	13	N/A
2 Stages Combined Suction (5 to 95MPa)	20	5	N/A
Tube-Trailer Direct Vehicle Fill Pressure [MPa]	44	13	N/A

- Fueling parameters

Fueling Protocol	Value
SAE Fill Pressure Ramp Rate @25°C Ambient, for 4-7 kg Tank Capacity [MPa/min]	18.5
Final Vehicle Tank Pressure [MPa] (Typical State Of Charge at 25°C ambient)	81 (96%)
Leak Checks Duration for Every 20MPa Rise [sec]	10
Lingering Time Between Fills [sec]	120
Number of Back-To-Back Fills During Peak Hour	5

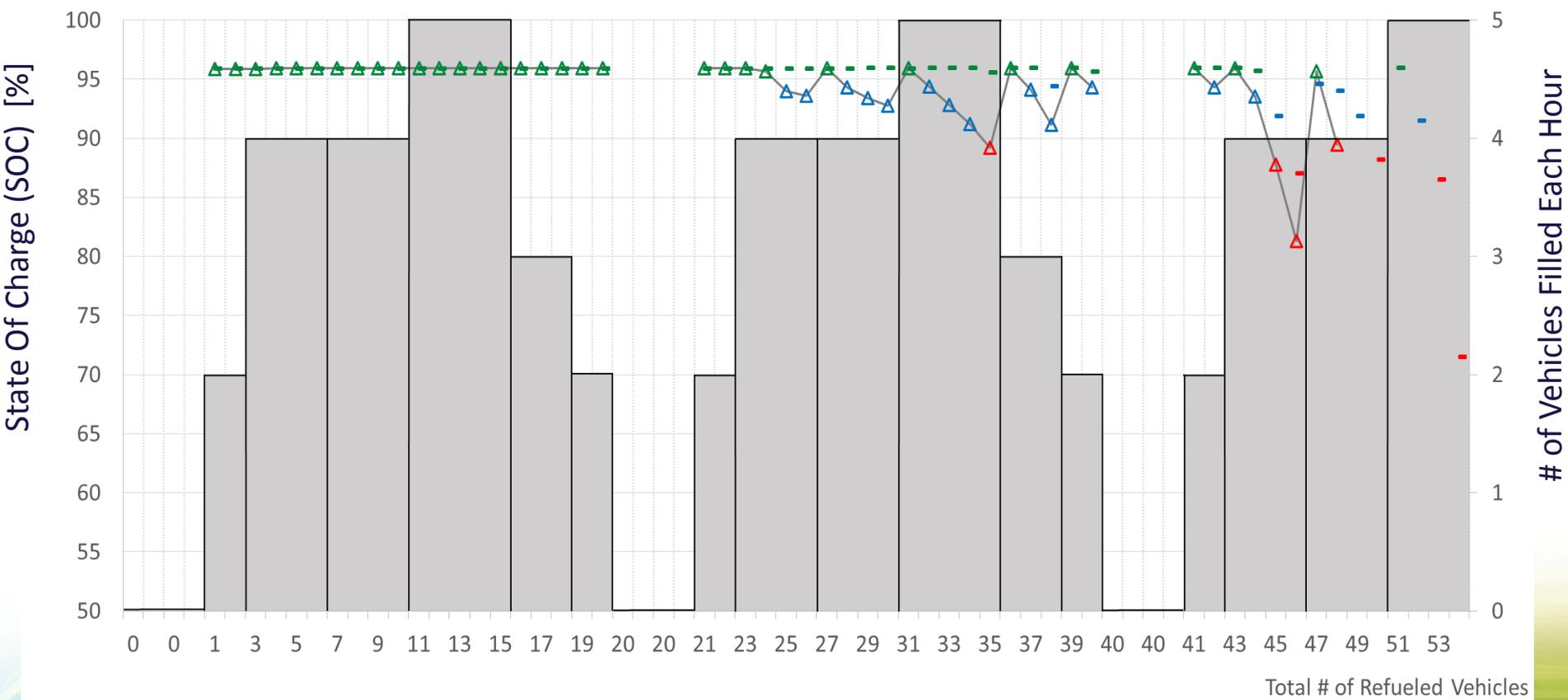
Simulated Station Performance -Accomplishments



➤ Fill operation with 5.0 kg fills and 3-bank buffer storage (1-hose)

▲ Baseline operation
 ■ Consolidation operation

Green → 95% < SOC (i.e., Full Charge)
 Blue → 95% > SOC > 90%
 Red → 90% > SOC



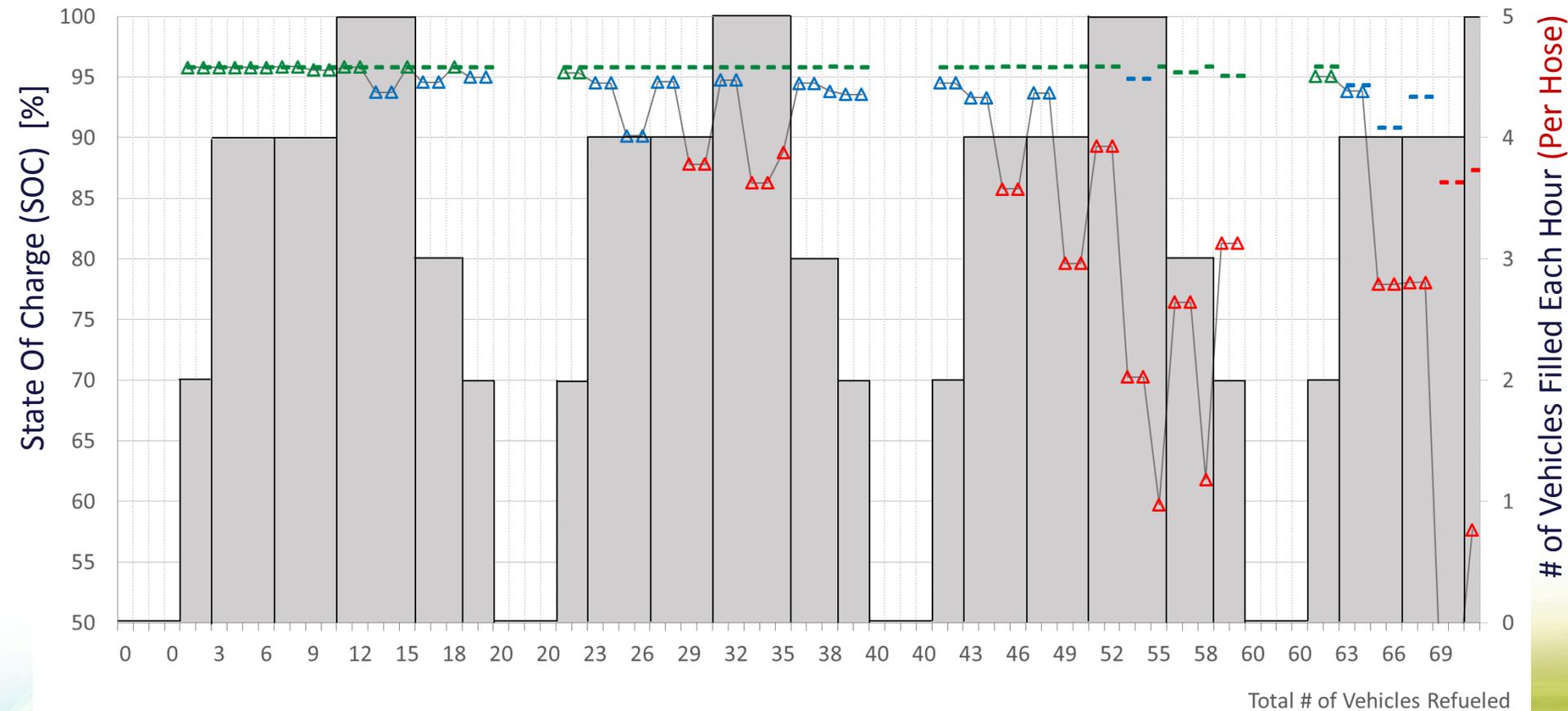
Simulated Station Performance -Accomplishments



➤ Fill operation with 3.7 kg fills and 3-bank buffer storage (2-hose)

▲ Baseline operation
 ■ Consolidation operation

Green → 95% < SOC (i.e., vehicle fill)
 Blue → 95% > SOC > 90% (i.e. partial vehicle fill)
 Red → 90% > SOC (i.e. partial vehicle fill)



Total # of Vehicles Refueled

of Vehicles Filled Each Hour (Per Hose)

Simulated Station Performance - Accomplishments



➤ Fill operation with 5.0 kg fills and 4-bank buffer storage (2-hose)

△ Baseline operation
■ Consolidation operation

→ 95% < SOC (i.e., Full Charge)
→ 95% > SOC > 90%
→ 90% > SOC

