H2FIRST

Hydrogen Fueling Infrastructure Research and Station Technology

Consolidation

Danny Terlip*	National Renewable Energy Lab
Amgad Elgowainy	Argonne National Lab
Krishna Reddi	Argonne National Lab
Kareem Afzal	PDC Machines Inc

**Presenter*

8 June 2017

Project ID# PD133

Overview

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

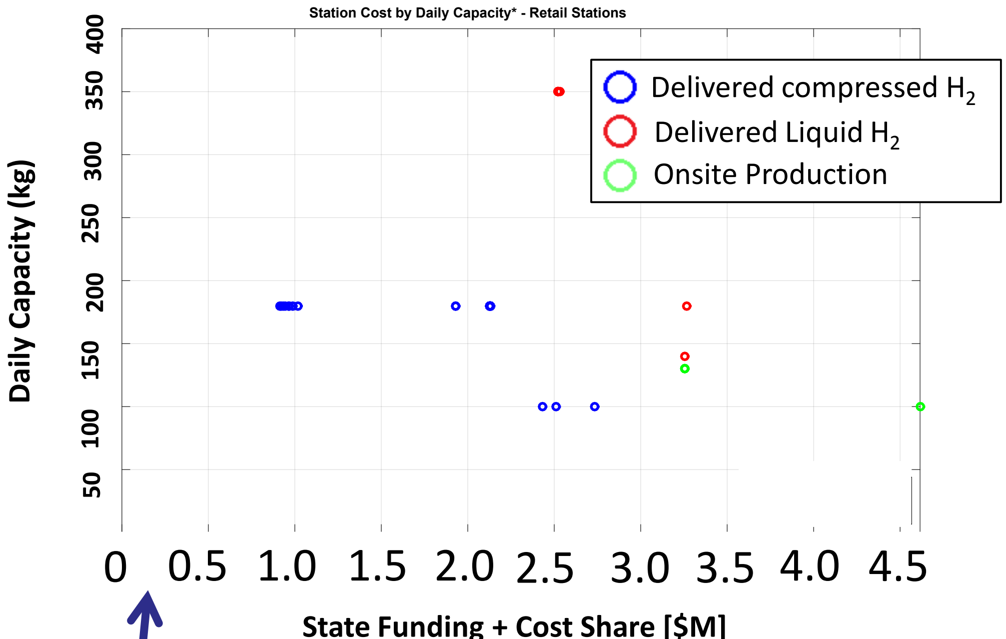
Partners

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

Problem Statement

Hydrogen station capital costs are too expensive

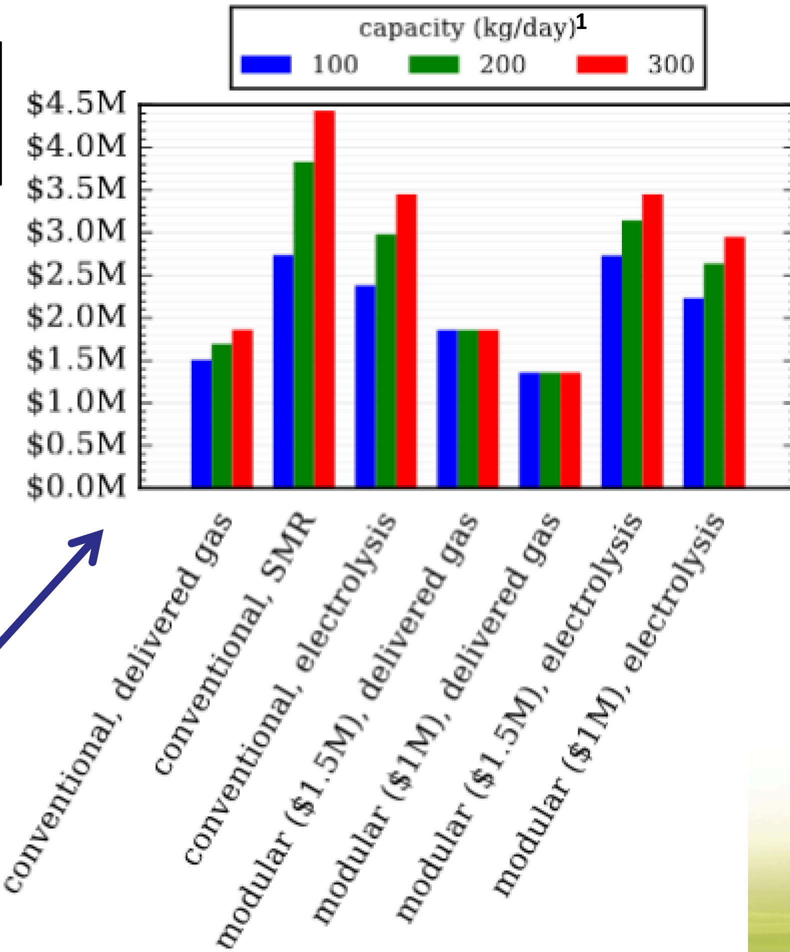
Hydrogen cost to break even in 7 years requires selling hydrogen at > $14/kg[1]



***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

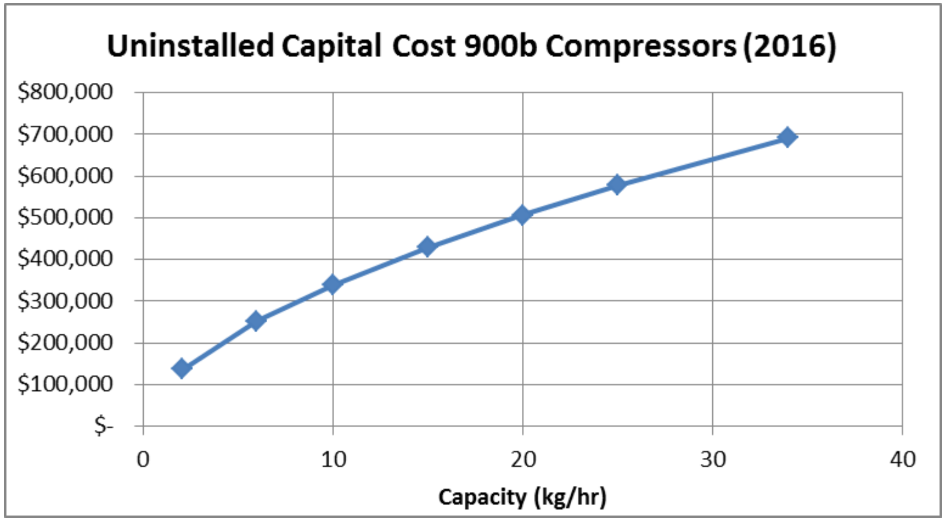


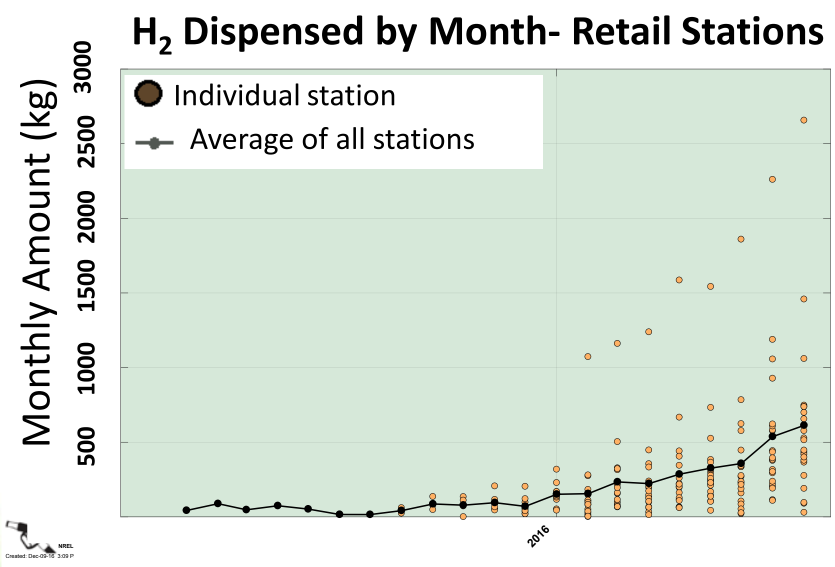
[1]Hecht and Pratt, "Comparison Of conventional vs. modular hydrogen refueling stations, and on-site production vs. delivery"

Current Status

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

Field data show station throughput is strongly increasing

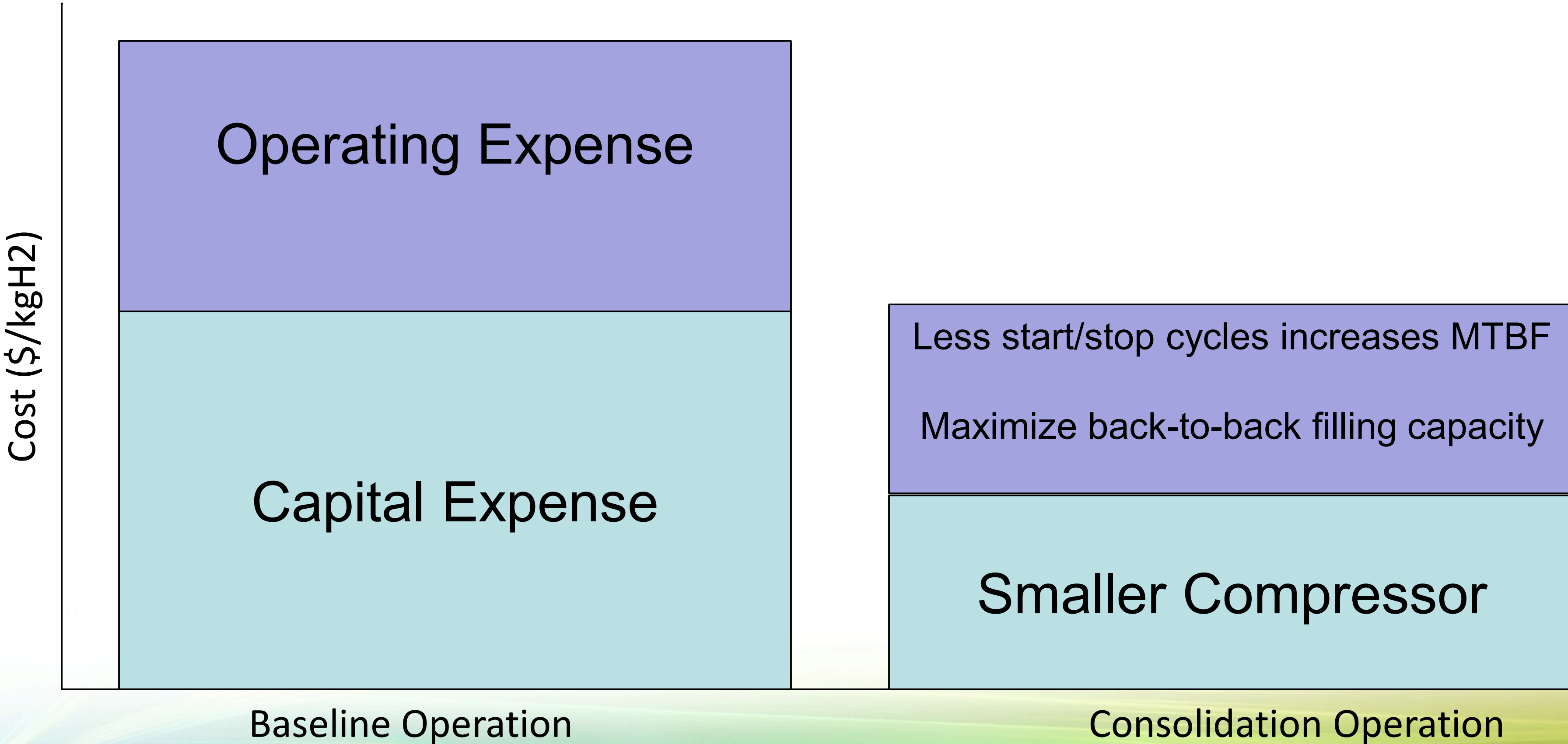




http://www.nrel.gov/hydrogen/images/cdp-retail-infr-19.jpg

Reducing Capital Costs

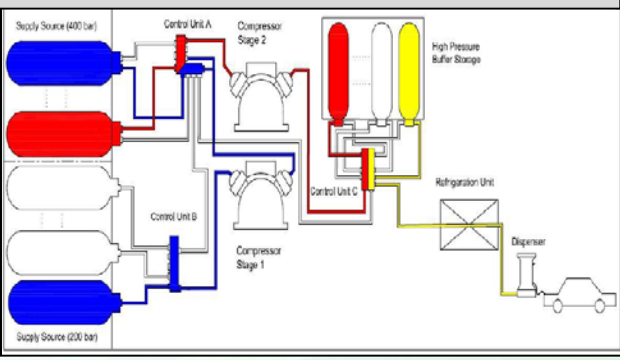
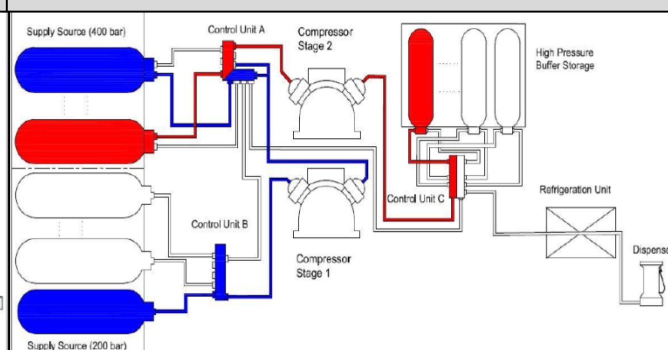
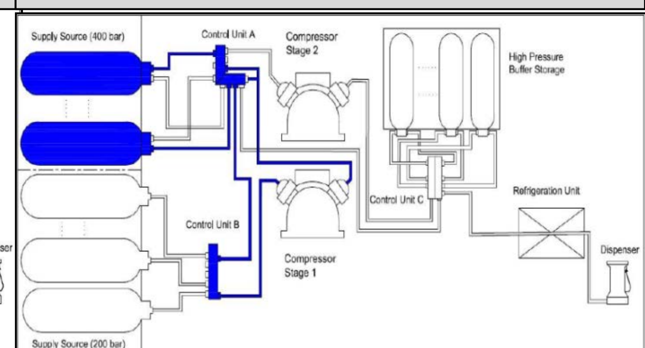
<u>ANL Consolidation Algorithm</u> projected to reduce the compression contribution to hydrogen cost (in terms of $/kgH2) by approximately 50%



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]**

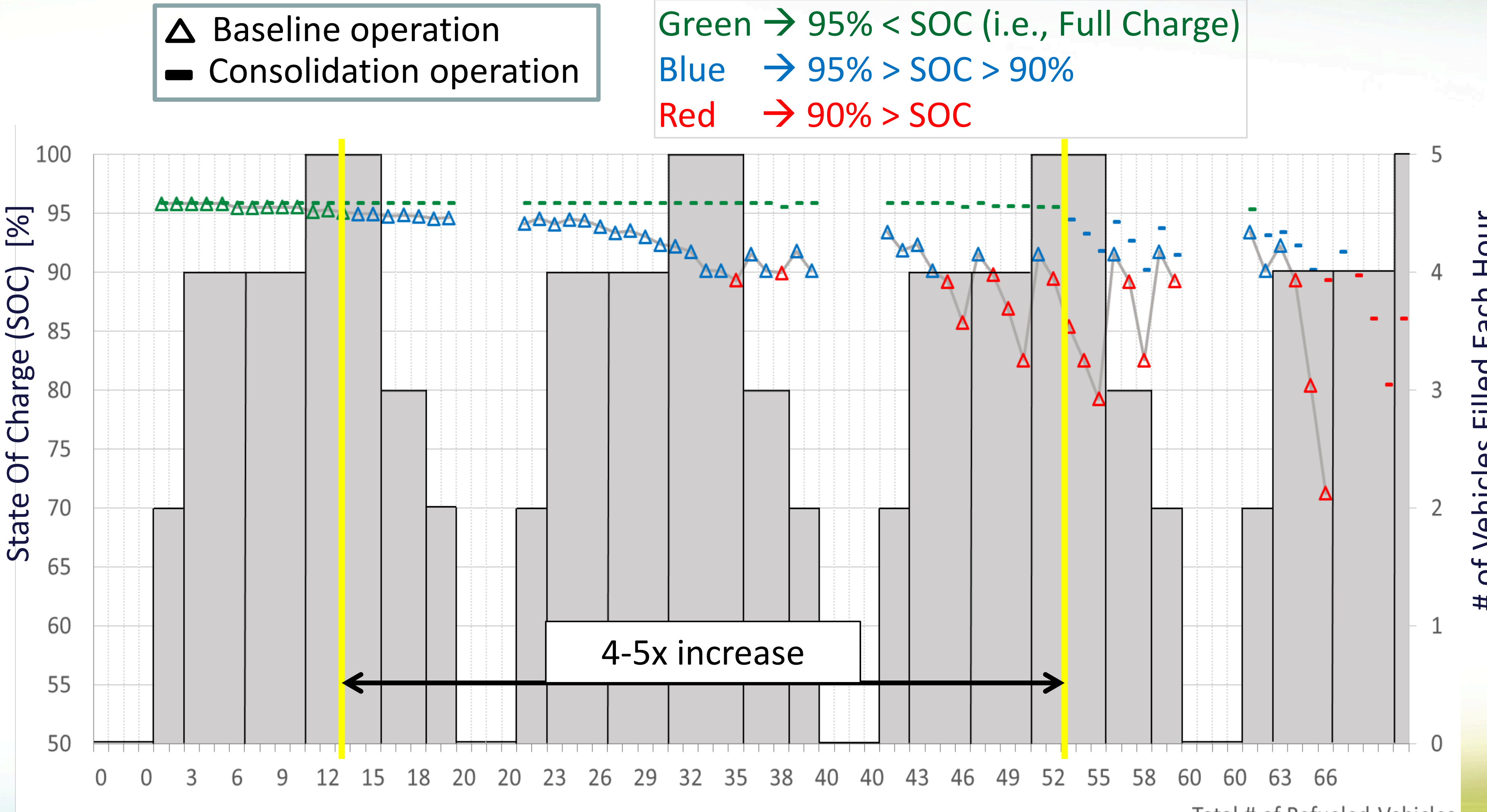
Consolidation algorithm defined to lower capital costs at hydrogen stations

Compress MP/HP tanks while filling from HP	Compress MP/HP tanks when not filling	Consolidate MP tanks when LP empty
		

1. Elgowainy, et. al. "Tube-trailer consolidation strategy for reducing hydrogen refueling station costs". International Journal of Hydrogen Energy, December 2014. (Vol. 39, Issue 35, Pages 20197–20206),

Approach - Simulated Consolidation Algorithm

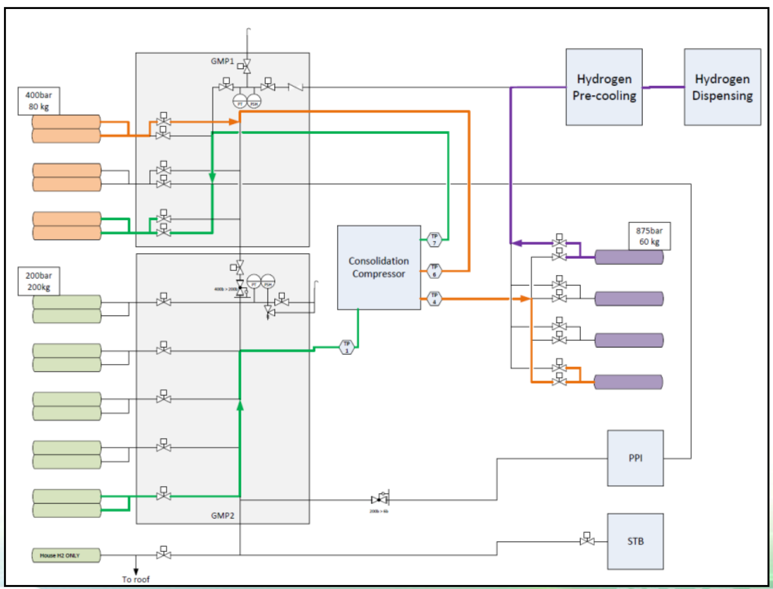
Simulation of station shows that consolidation enables 4-5x increase in number of complete vehicle fills possible



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

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
  - <u>**Developing control algorithm and capability through this project**</u>
- **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

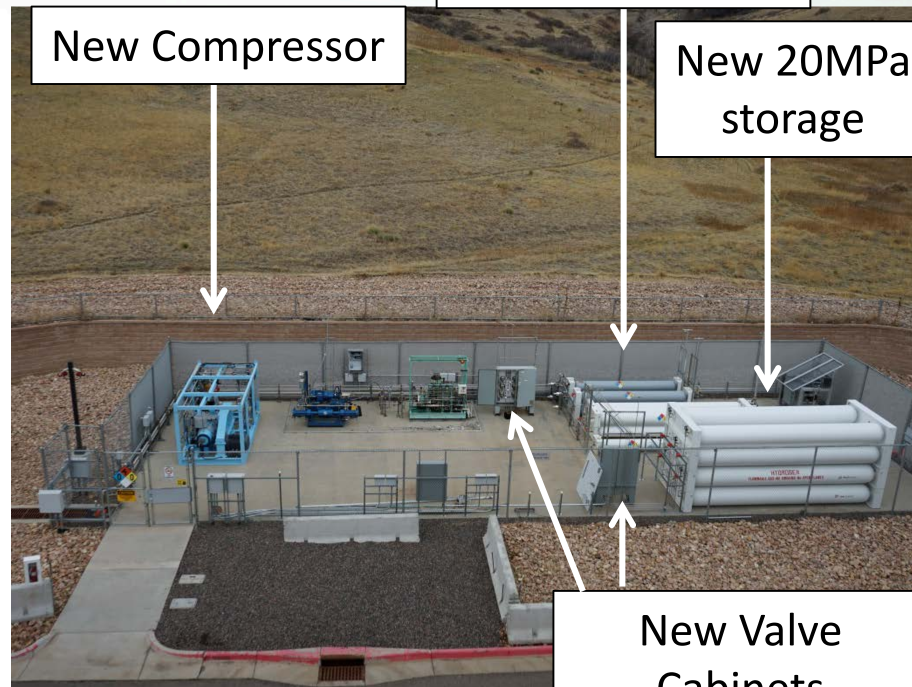
  FUTURE

Accomplishments – Build out completed

H2FIRST

HITRF 2014

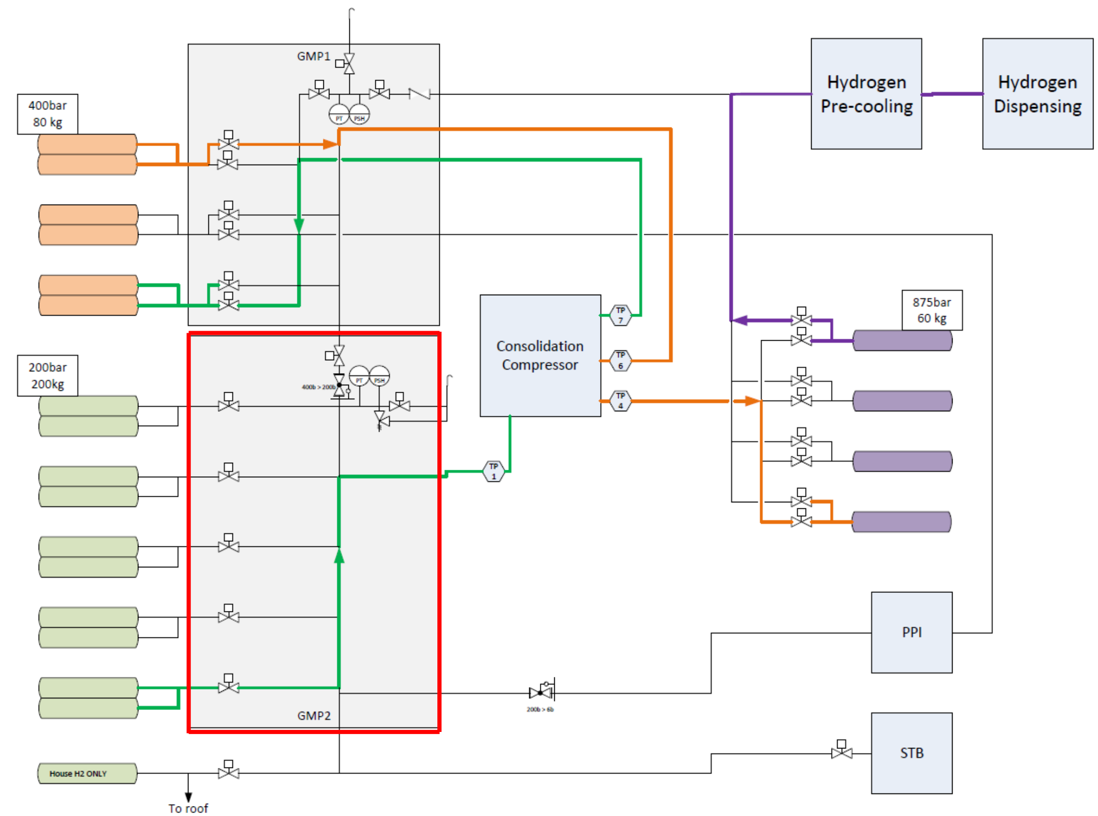
HITRF 2017



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

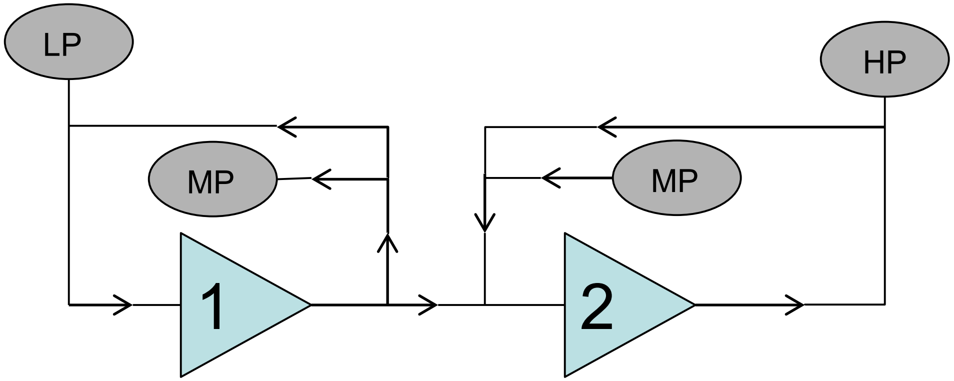
Progress – Low Pressure Gas Management Panel Design and Construction

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

Proposed Future Work

- 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

Technology Transfer Activities

- 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

Summary

- 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

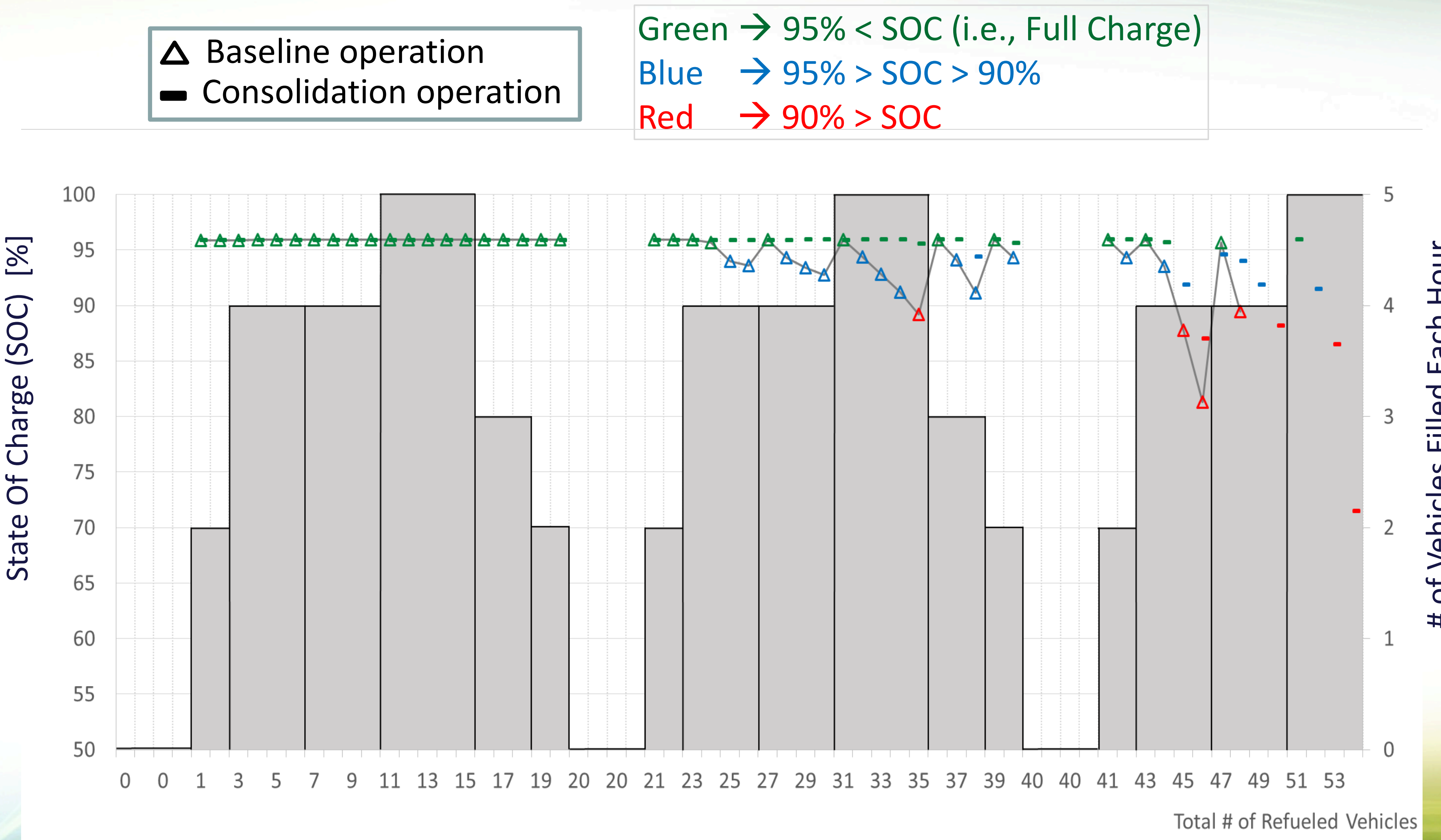
Process Limits	Max	Min	MAWP
High Pressure Cascade Pressure [MPa]	91	42	93
40 MPa Storage Pressure [MPa]	44	5	45.9
20 MPa Storage Pressure [MPa]	26	2	27.5
1st Stage Independent Suction (2 to 40 MPa)	20	2	N/A
2nd Stage Independent Suction (13 to 95 MPa)	40	13	N/A
2 Stages Combined Suction (5 to 95MPa)	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^{o}C Ambient, for 4-7 kg Tank Capacity [MPa/min]	18.5
Final Vehicle Tank Pressure [MPa] (Typical State Of Charge at 25^{o}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

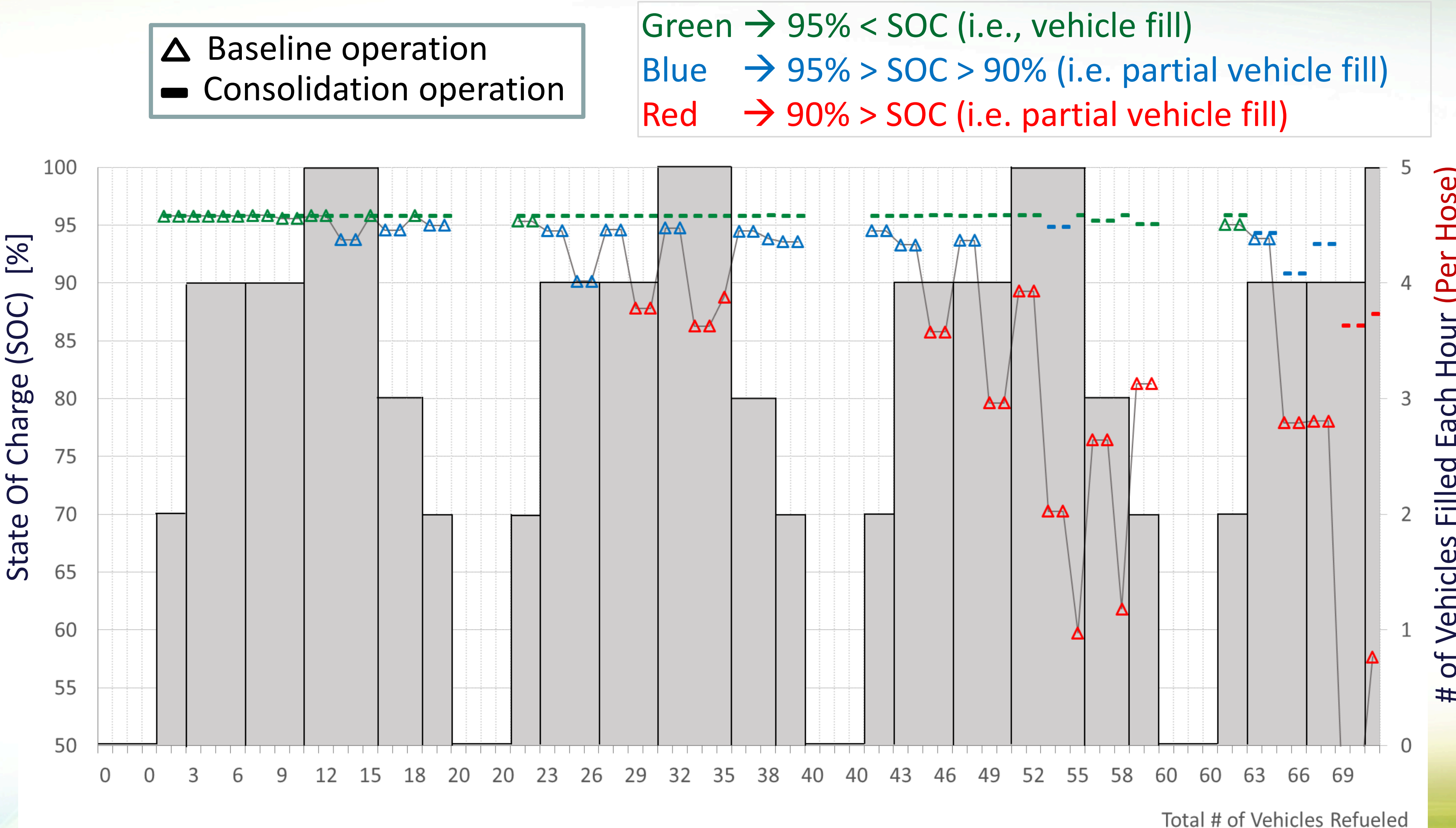
- Fill operation with 5.0 kg fills and 3-bank buffer storage (1-hose)



Simulated Station Performance -Accomplishments

H2FIRST

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



Simulated Station Performance -Accomplishments

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