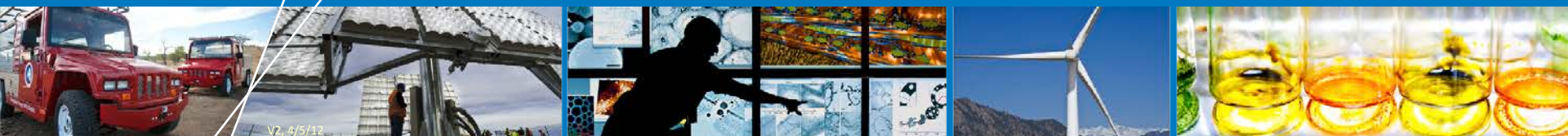


# Final Results from U.S. FCEV Learning Demonstration



**EVS-26**

**Session B1**

**Keith Wipke, Sam Sprik, Jennifer Kurtz, Todd Ramsden, Chris Ainscough, Genevieve Saur**

**May 7, 2012: Los Angeles, CA**

**NREL/PR-5600-55347**

This presentation does not contain any proprietary, confidential, or otherwise restricted information

# Fuel Cell Electric Vehicle Learning Demo

## Project Objectives, Relevance, and Targets

### • Objectives

- Validate H<sub>2</sub> FC Vehicles and Infrastructure in Real-World Setting
- Identify Current Status and Evolution of the Technology
- Objectively Assess Progress Toward Targets and Market Needs
- Provide Feedback to H<sub>2</sub> Research and Development
- Publish Results for Key Stakeholder Use and Investment Decisions

### Key Targets

Performance Measure	Interim (2009)*	Ultimate (2020)
Fuel Cell Stack Durability	2000 hours	5000 hours
Vehicle Range	250+ miles	300+ miles
Hydrogen Cost at Station	\$3/gge	\$2-4/gge**

*\*Project extended 2 years through 2011; \*\*Previously \$2-3/gge for 2015*



APC/Shell Pipeline station, Torrance, CA.  
Photo by Michael Penev, NREL

*Details of each of these 3 results in technical backup slides (previous EVS)*

# NREL's Technology Validation Approach

## Supporting Both DOE/Public as Well as Technology Developers

Bundled data (operation & maintenance/safety) delivered to NREL quarterly

Internal analysis completed quarterly

### HSDC

NREL's Hydrogen Secure Data Center

Results

Public

CDPs

DDPs

Confidential

### Detailed Data Products (DDPs)

- Individual data analyses
- Identify individual contribution to CDPs
- Shared every six months only with the partner who supplied the data<sup>1</sup>

### Composite Data Products (CDPs)

- Aggregated data across multiple systems, sites, and teams
- Publish analysis results every six months without revealing proprietary data<sup>2</sup>

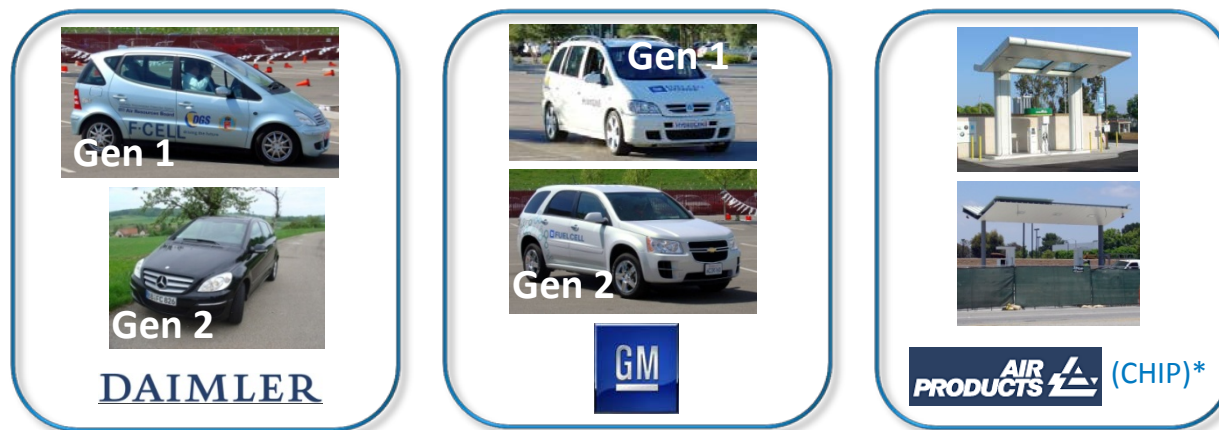
1) Data exchange may happen more frequently based on data, analysis, & collaboration

2) Results published via NREL Tech Val website, conferences, and reports ([http://www.nrel.gov/hydrogen/proj\\_learning\\_demo.html](http://www.nrel.gov/hydrogen/proj_learning_demo.html))

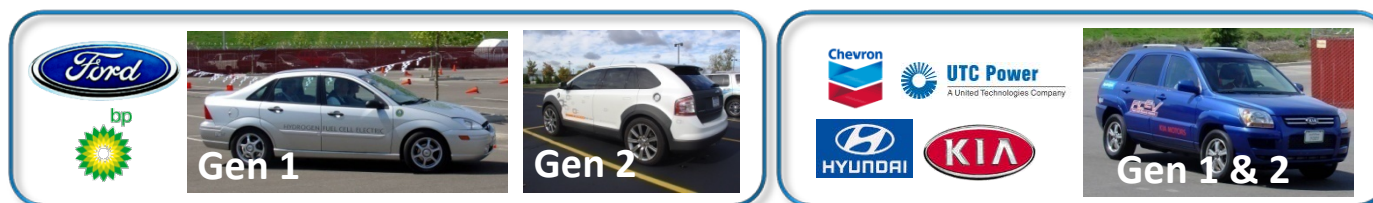
# Industry Partners: Collaborative Relationship, Working Through Details of Analysis, was Critical to Success

FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12
RFP	Startup	Operation, Data Collection, and Analysis							

Collaboration with Daimler, GM, and Air Products;  
Data in the Last Year (through Sept.) came from These 3 Companies



♦ Ford/BP and Chevron/Hyundai-Kia Participated Through 2009



\*CHIP = California Hydrogen Infrastructure Project

# 2<sup>nd</sup> Generation Vehicles Demonstrated Technology Improvements Over Gen 1

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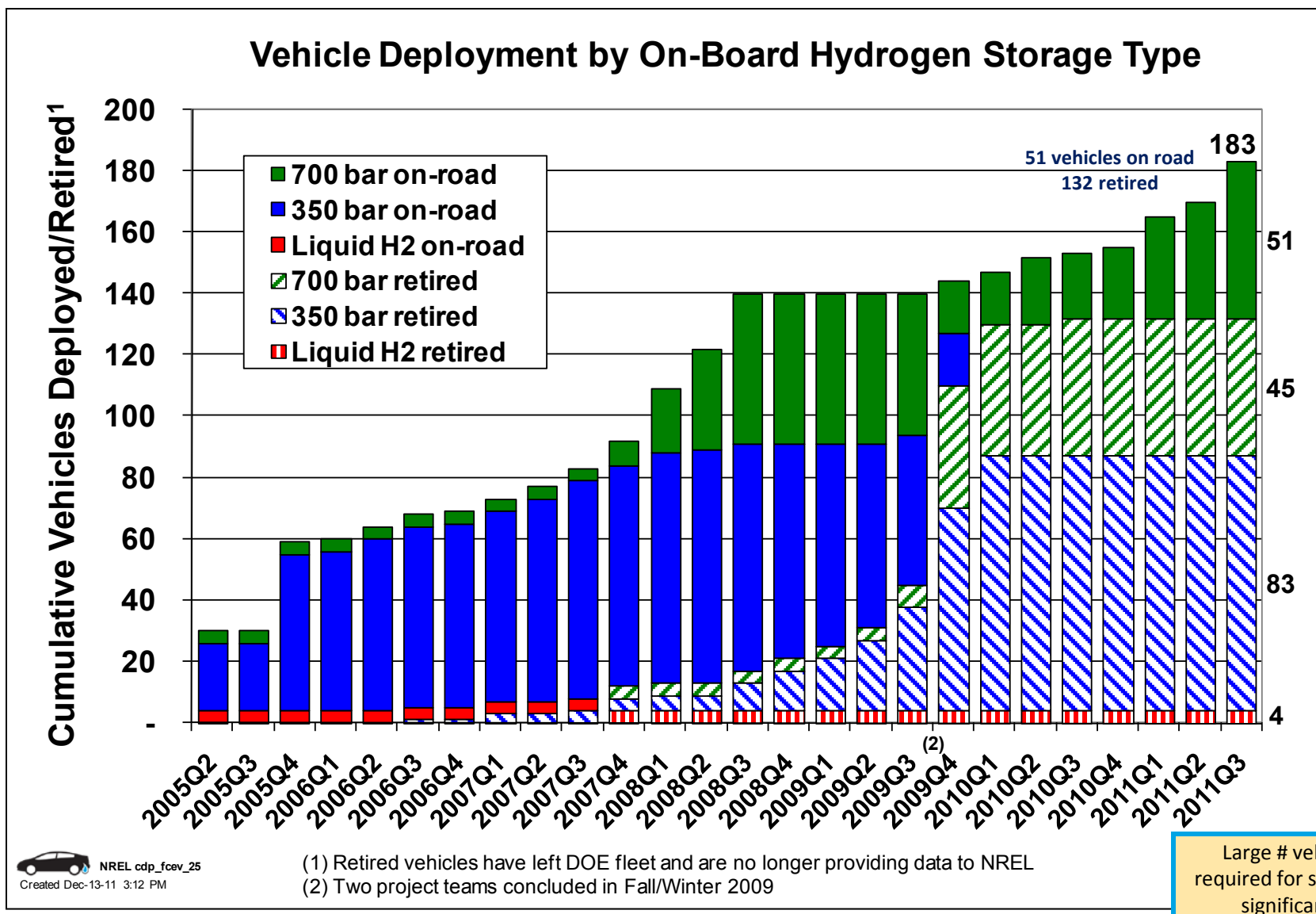
## Generation 1 Vehicles

- FC not freeze-capable
- ~2003 stack technology
- Storage: liquid H<sub>2</sub> & 350 and 700 bar
- Range: 100-200 miles
- Efficiency: 51-58% at ¼ power

## Generation 2 Vehicles

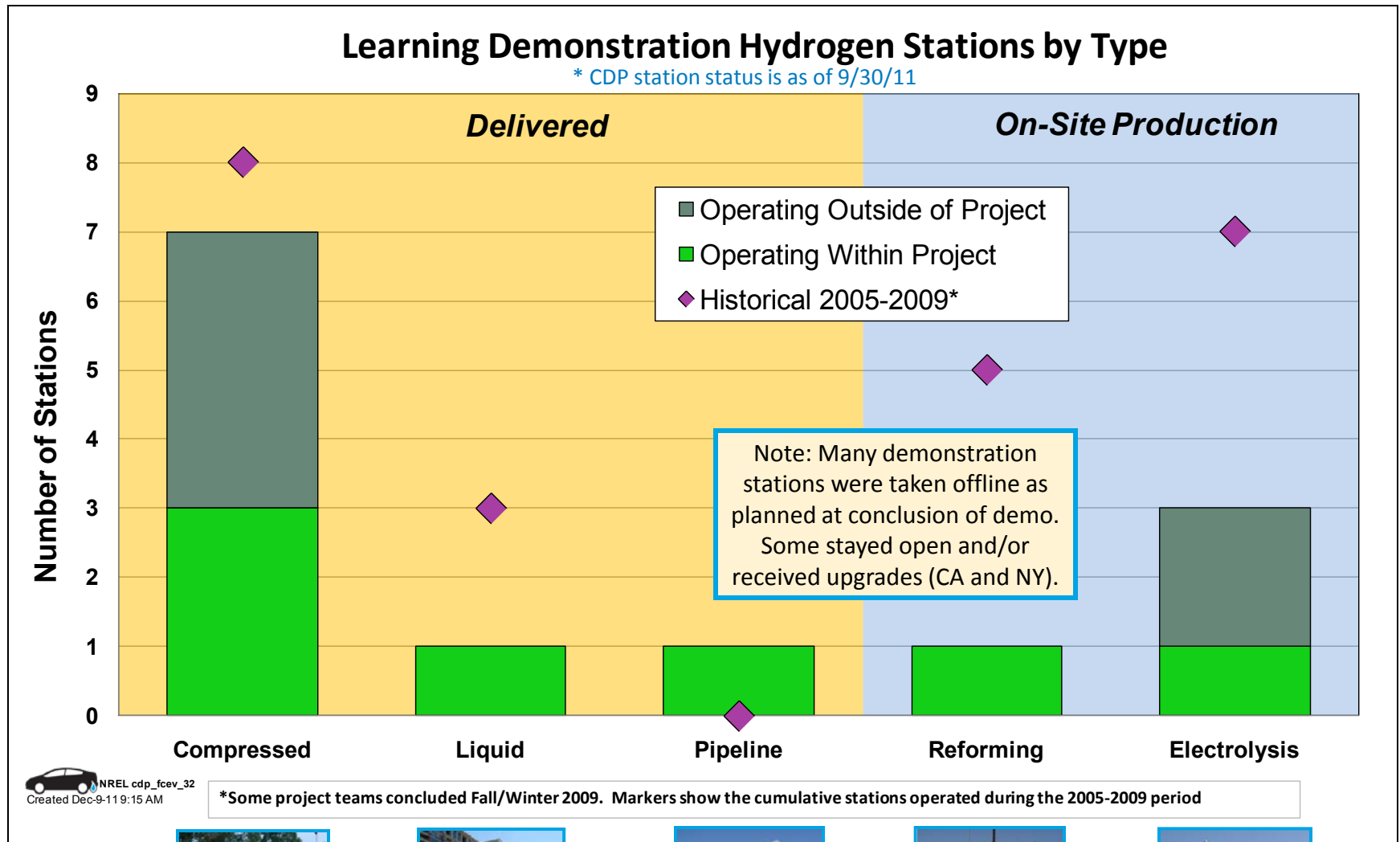
- FC freeze-capable
- ~2007-2009 stack tech.
- Storage: All 700 bar
- Range: 200-250 miles
- Efficiency: 53-59% at ¼ power
- Longer FC durability

# Vehicle Status: All Project Vehicles in the Last Two Years Were Using 700 bar Storage

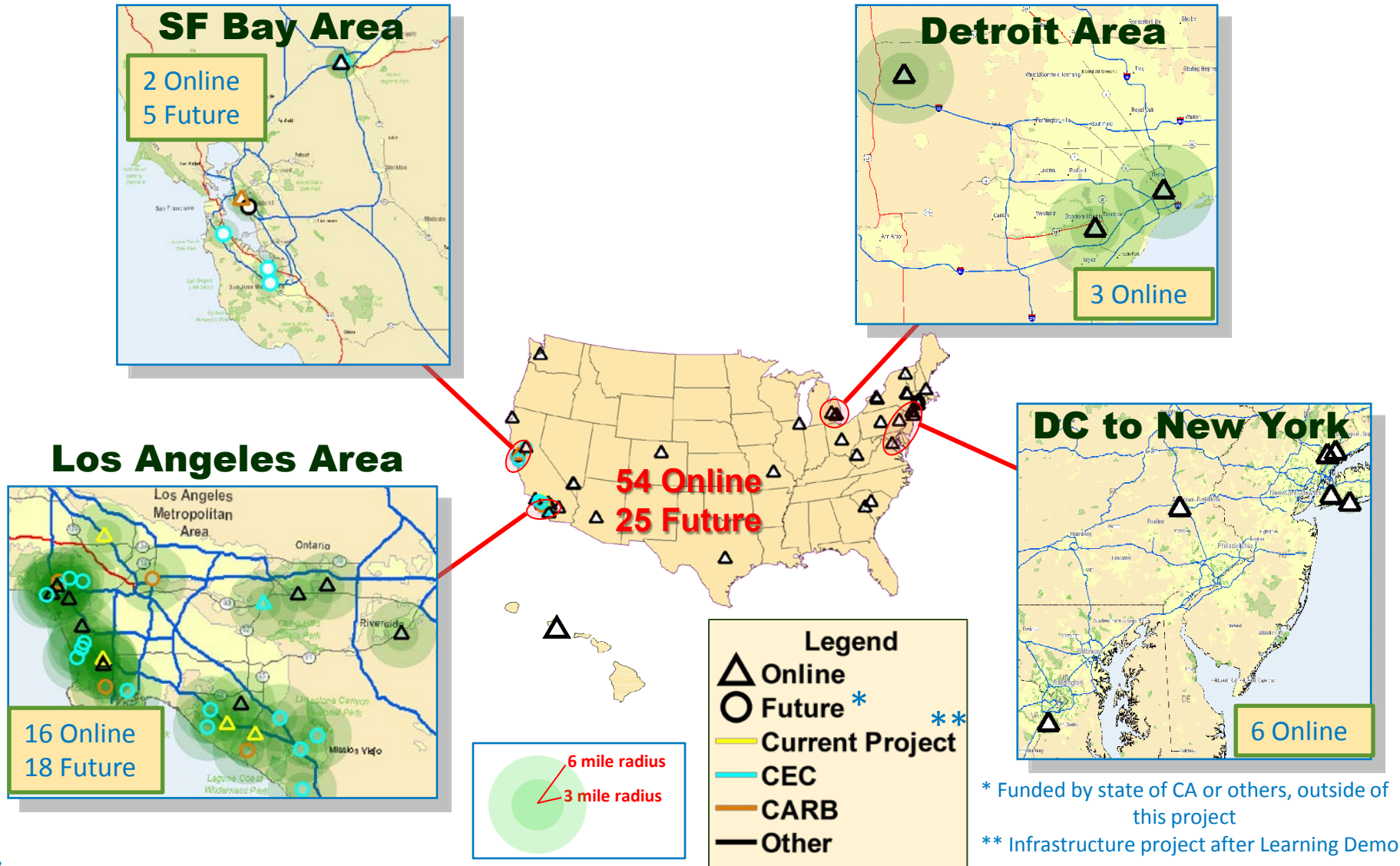




# Five Types of Fueling Stations Evaluated

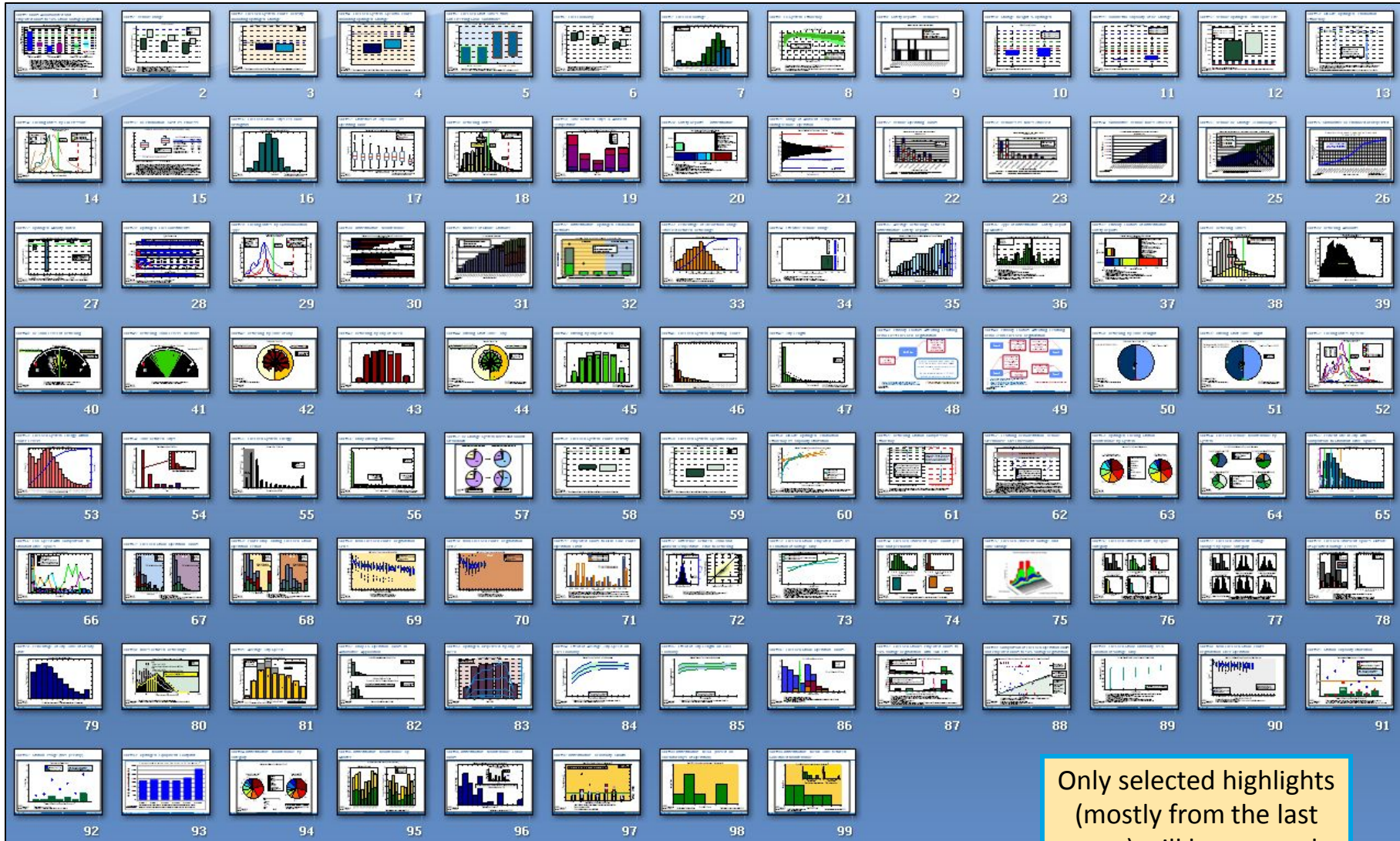


# Infrastructure Status: Out of 25 Project Stations, 13 Were Still Operational at End of Project (6 outside of DOE project)



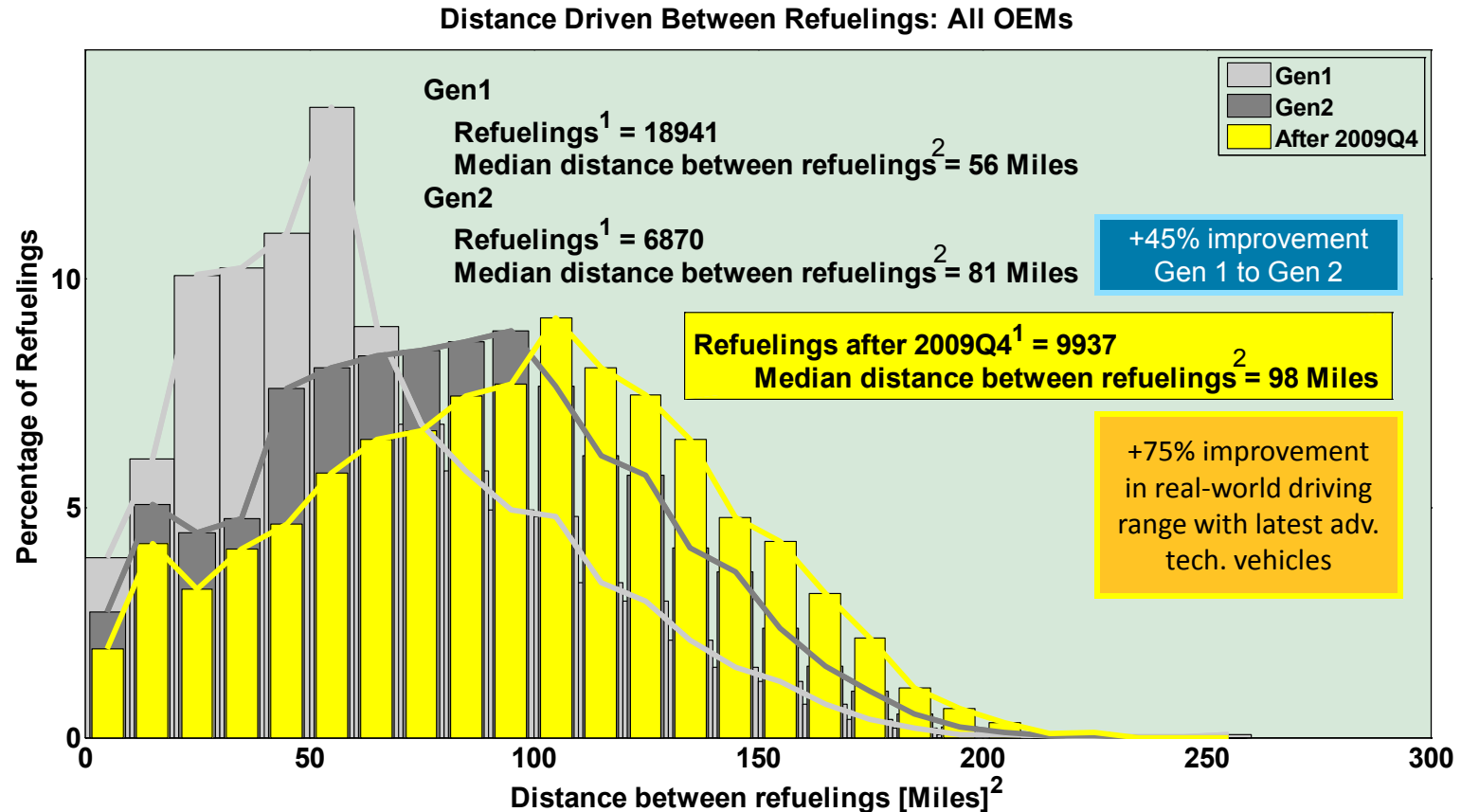


# Total of 99 CDPs Published (40 Winter 2011 CDPs)

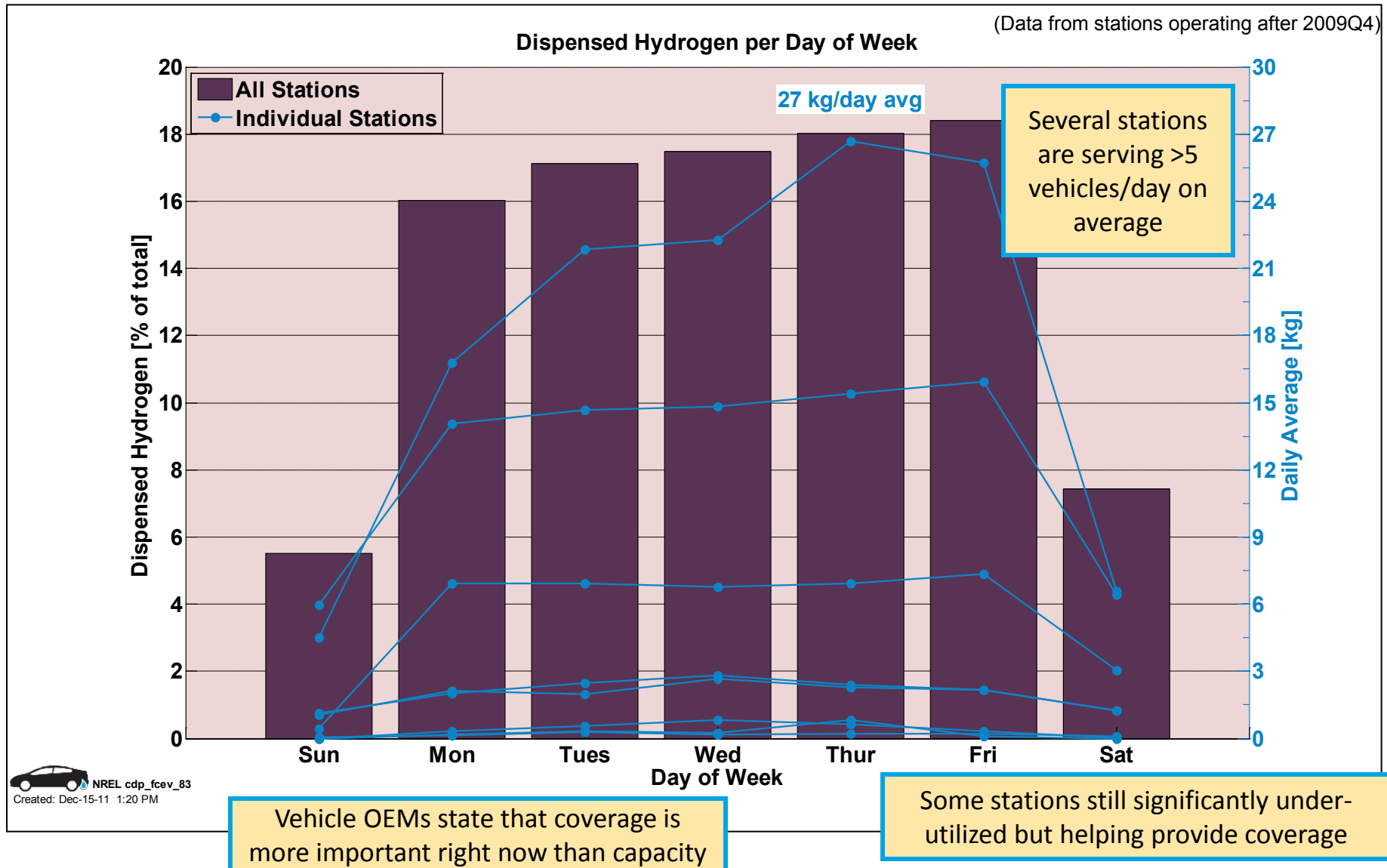


Only selected highlights  
(mostly from the last  
year) will be covered

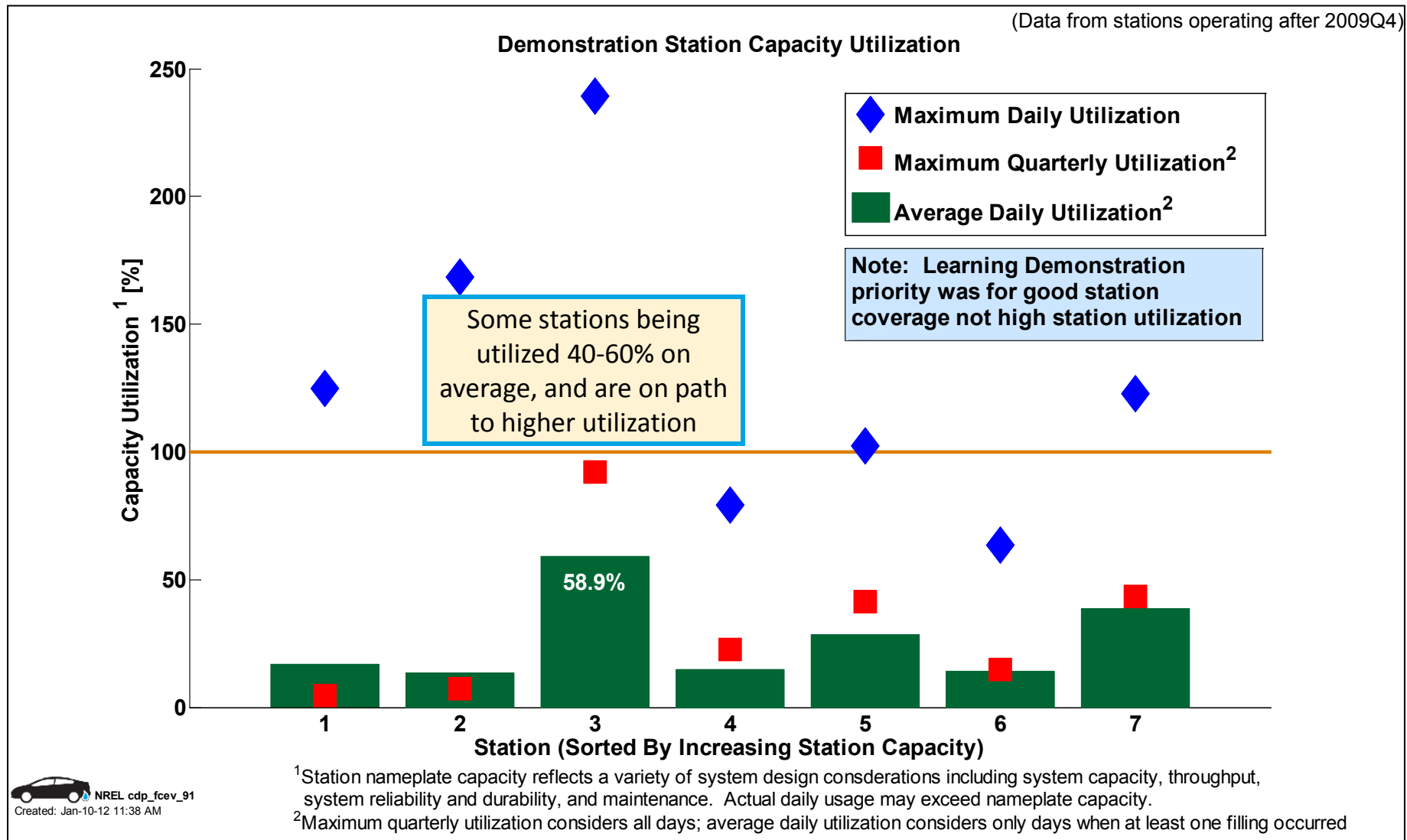
# Vehicles Show Continued Improvement in Distance Between Fuelings (Real-World)



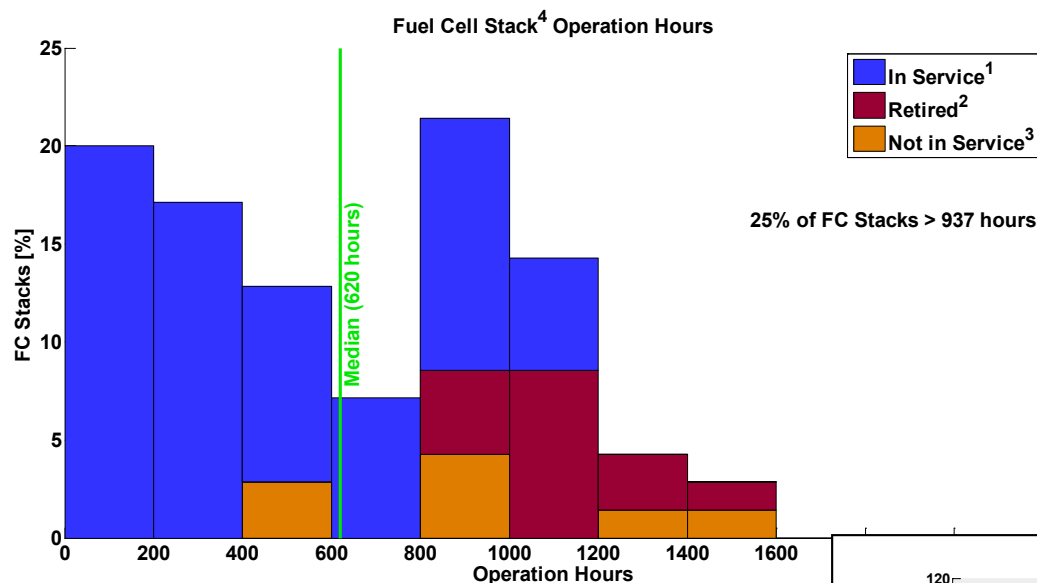
# INFRASTRUCTURE: New Infrastructure CDP Gives Insight Into Specific Fueling Usage Patterns



# INFRASTRUCTURE: While Station Focus is on Coverage, We've Tracked Capacity Usage as Baseline for Future



# FC DURABILITY: Evaluated FC Durability Data from FCEVs After 2009Q4

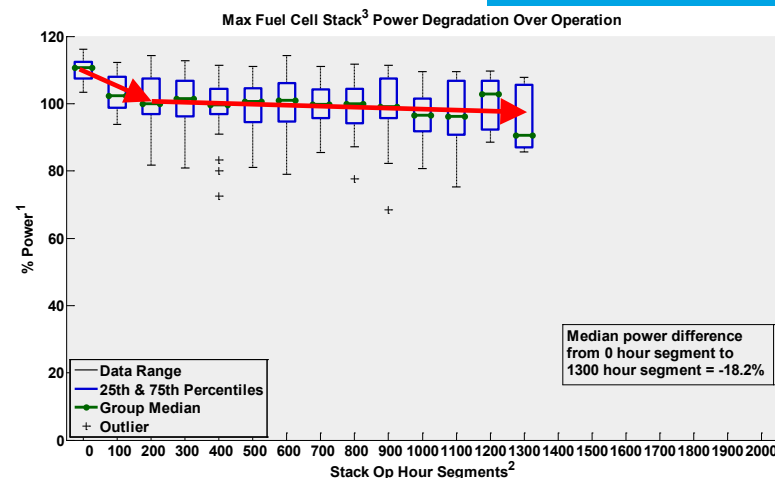


- 1) Stacks that are in service and accumulating operation hours.
- 2) Stacks retired due to low-performance or catastrophic failure.
- 3) Indicates stacks that are no longer accumulating hours either a) temporarily or b) have been retired for non-related issues or c) removed from DOE program.
- 4) Only includes systems operating after 2009Q4.

NREL cdp\_fcenv\_96  
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Some stacks operated over 1,400 hours, but half were still below 600 hours

Recent data from stacks shows knee in FC power degradation curve at ~200 hours

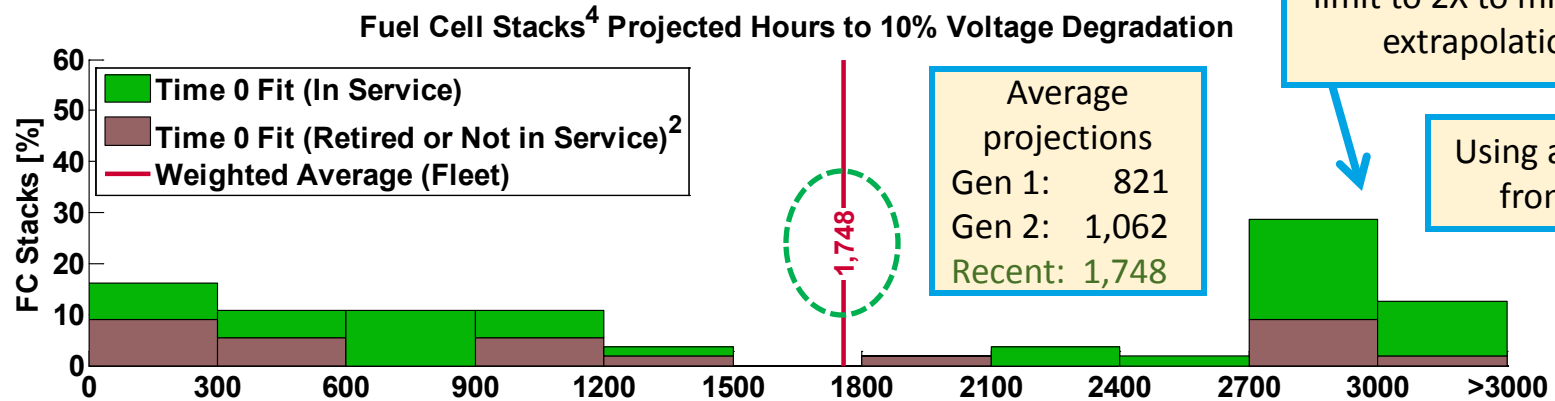


- 1) Normalized by fleet median value at 200 hours.
- 2) Each segment point is median FC power (+/-50 hrs). Box not drawn if fewer than 3 points in segment.
- 3) Only includes systems operated after 2009Q4.

NREL cdp\_fcenv\_90  
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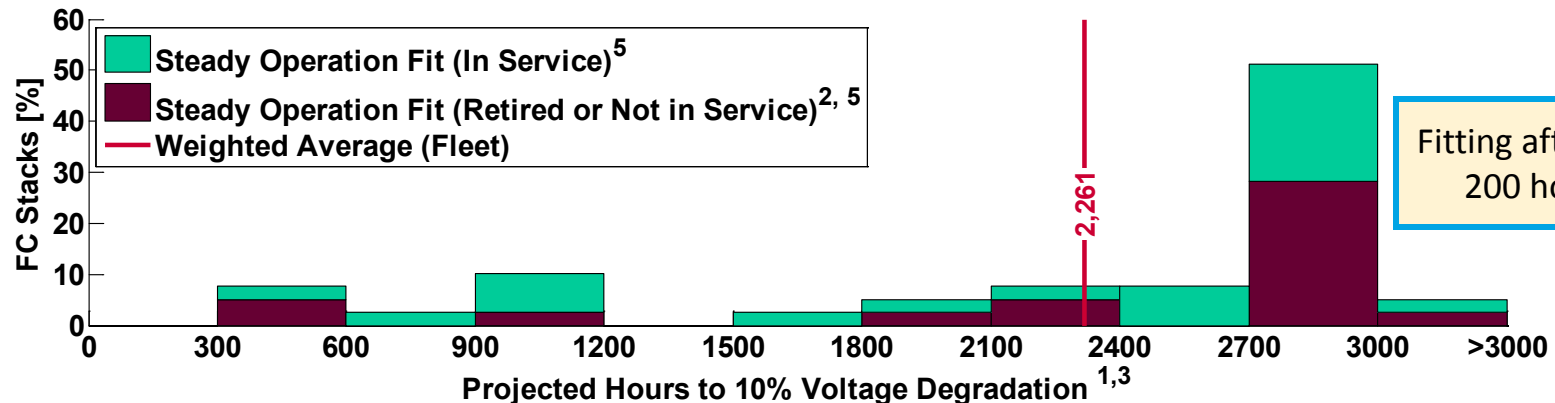


# FC DURABILITY: Projected Fuel Stack Durability to 10% Voltage Degradation; Two Fits



Many stacks have projections that we limit to 2X to minimize extrapolation

Using all data from t0



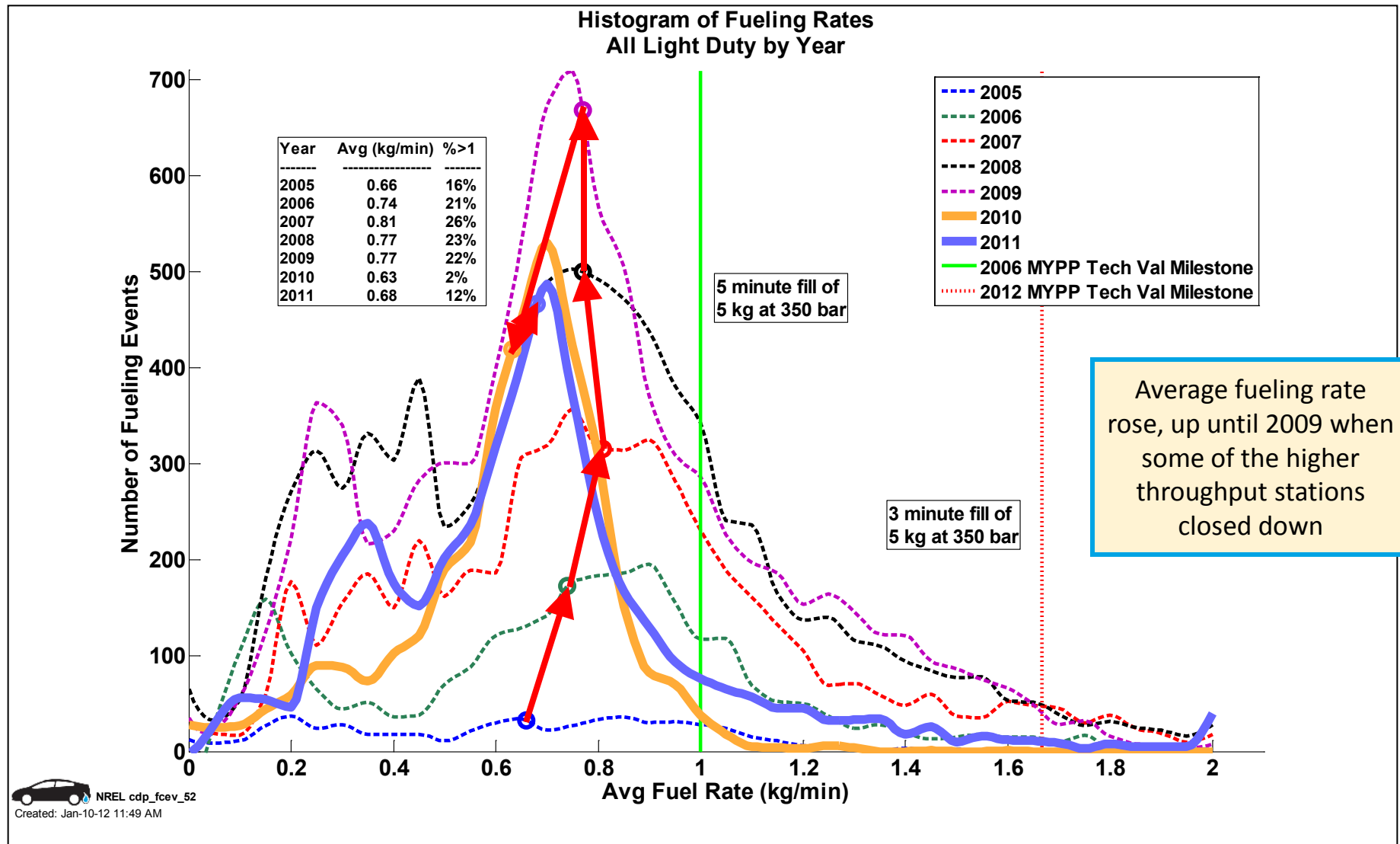
Fitting after first 200 hours

- 1) Projection using field data, calculated at high stack current, from operation hour 0 or a steady operation period. Projected hours may differ from an OEM's end-of-life criterion and does not address "catastrophic" failure modes.
- 2) Indicates stacks that are no longer accumulating hours either a) temporarily or b) have been retired for non-stack performance related issues or c) removed from DOE program.
- 3) Projected hours limited based on demonstrated hours.

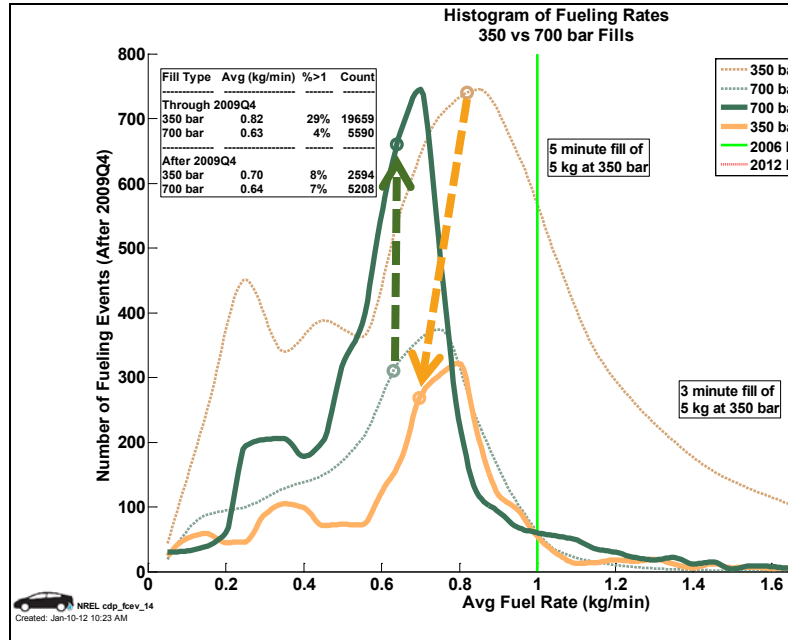
- 4) Only includes systems operating after 2009Q4.
- 5) Not all stacks have a steady operation fit which is calculated from data after 200 hr break-in period. The steady operation starting hour is the period after initial break-in where degradation levels to a more steady rate.

See technical backup for additional details in scatter plot

# FUELING: Tracked Fueling Rates by Year – Analyzed Trends as Stations Move to 700 bar as Standard



# FUELING: Evaluated Fueling Rates by Fill Pressure and Communication vs. Non-Communication



350 vs. 700 bar

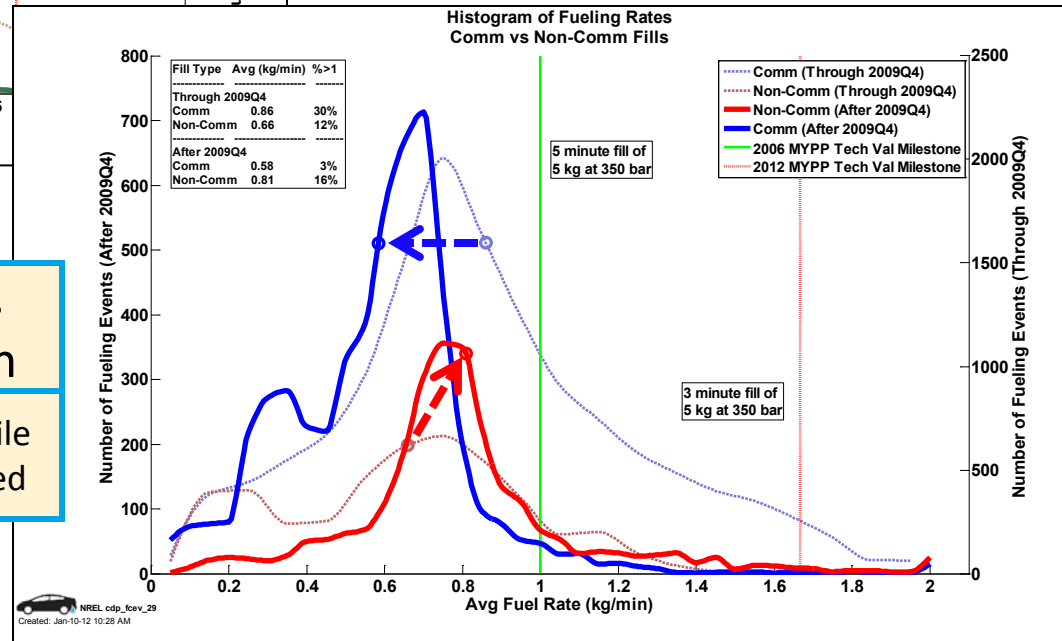
700 bar fueling rates holding constant at ~0.63 kg/min

350 bar fueling rates dropped from 0.82 to 0.70 kg/min

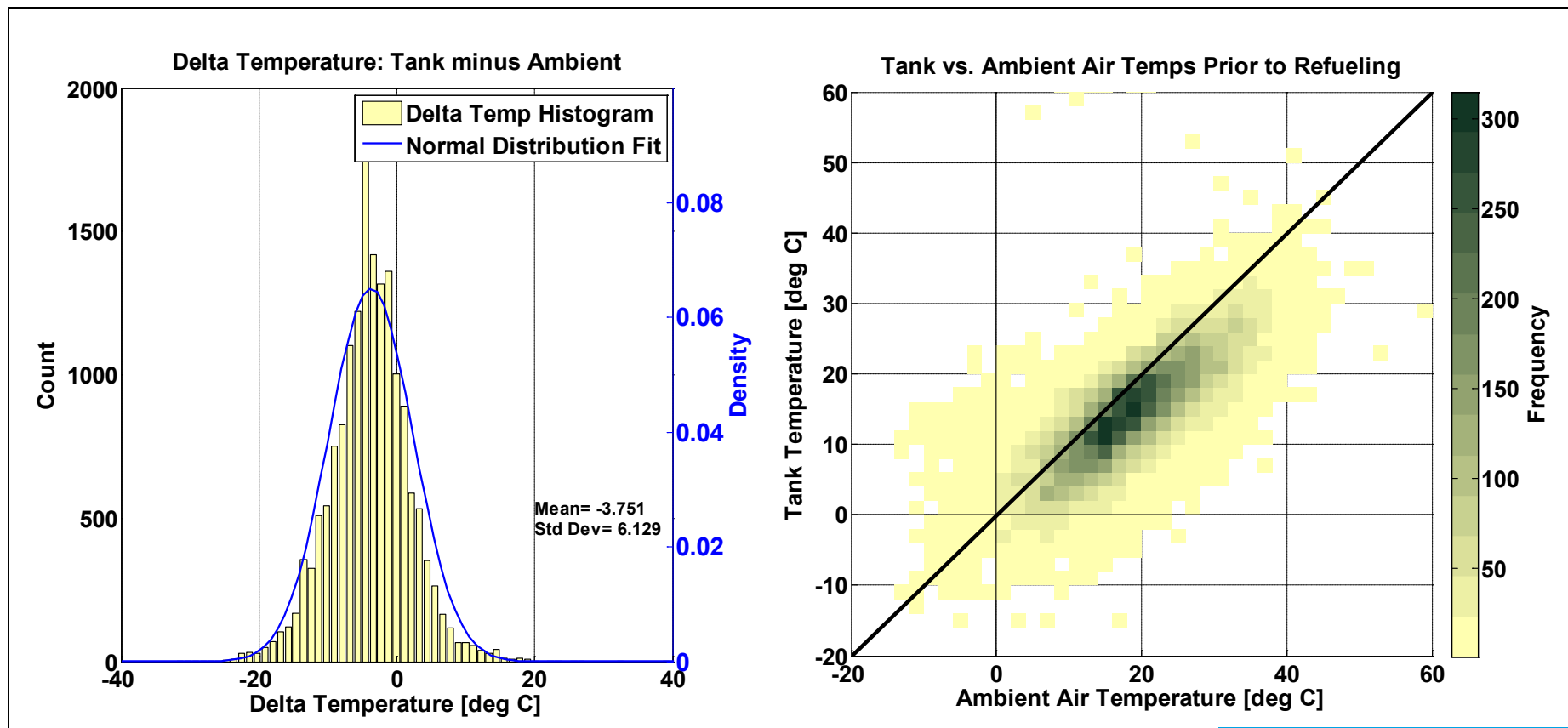
Fueling rates are still evolving due to changes in technology and protocols

Communication vs.  
non-communication

Comm. fill rates dropped while  
non-comm. fill rates increased



# STANDARDS: Analysis Results Informed R&D Activities and Codes and Standards Development



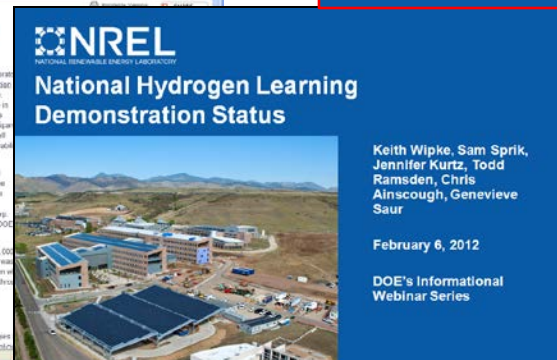
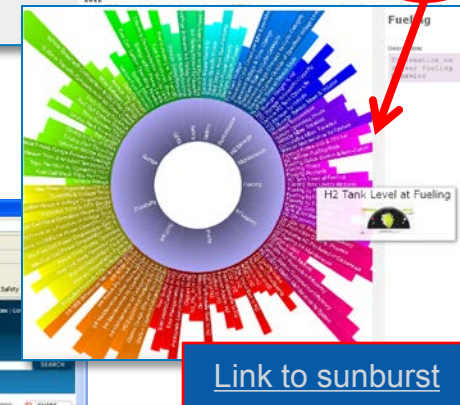
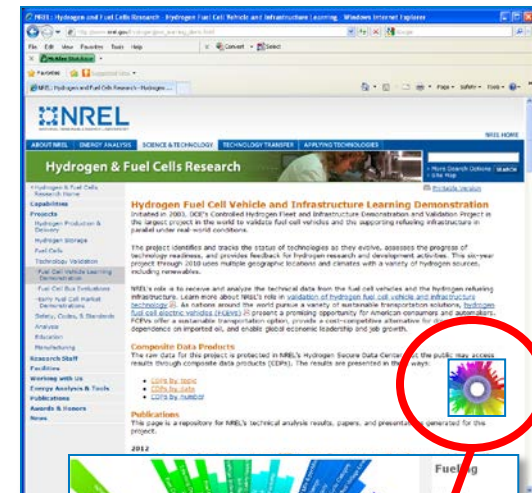
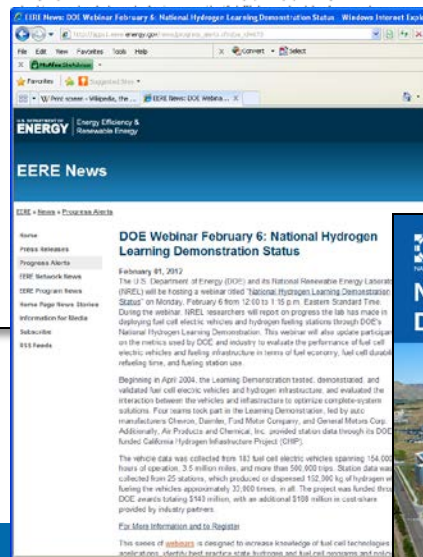
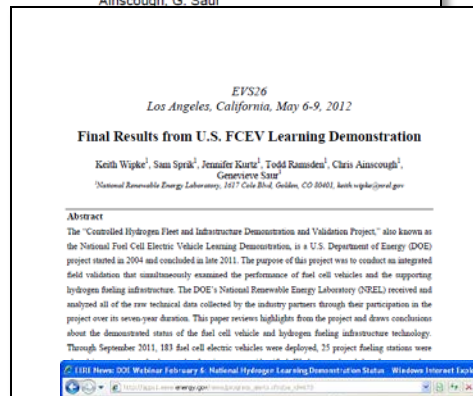
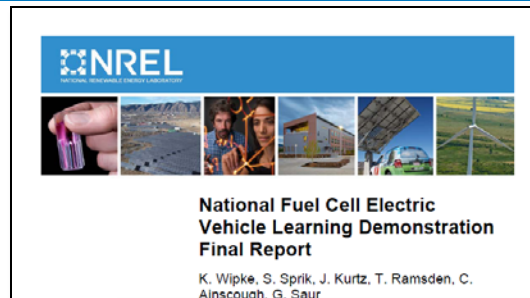
FCEVs arrive at station with a tank temperature that is 3.8 degrees C colder than ambient temp

- This CDP created in support of SAE J2601 related to refueling
- Temperatures are prior to refueling and exclude data within 4 hours of a previous fill
- The plot to the left excludes ambient temperatures less than -5 deg C

This result allowed participants in J2601 to use validated/realistic initial conditions to their computer models for tank temperature rise

# Final Project Results Communicated to Broad Audience via Multiple Paths

- Final report published in April and posted on NREL's web site
- EVS-26 paper
- Held public webinar
  - 260 participants (400 registered)
  - Active Q&A
- Created more interactive way to access CDP results from web site (now live)





# Summary of Key Technical Results

Vehicle Performance Metrics	Gen 1 Vehicle	Gen 2 Vehicle	2009 Target	After 2009Q4
<b>Fuel Cell Stack Durability</b>			2,000 hours	
Max Team Projected Hours to 10% Voltage Degradation	<b>1,807 hours</b>	<b><u>2,521</u> hours</b>		--
Average Fuel Cell Durability Projection	821 hours	1,062 hours		1,748 hours
Max Hours of Operation by a Single FC Stack to Date	2,375 hours	1,261 hours		1,582 hours
<b>Driving Range</b>			250 miles	
Adjusted Dyno (Window Sticker) Range	<b>103-190 miles</b>	<b>196-<u>254</u> miles</b>		--
Median On-Road Distance Between Fuelings	56 miles	81 miles		98 miles
<i>Fuel Economy (Window Sticker)</i>	42 – 57 mi/kg	43 – 58 mi/kg	no target	--
<i>Fuel Cell Efficiency at ¼ Power</i>	51 – 58%	53 – <u>59</u> %	60%	--
<i>Fuel Cell Efficiency at Full Power</i>	30 – 54%	42 – <u>53</u> %	50%	--
Infrastructure Performance Metrics			2009 Target	After 2009Q4
<b>H<sub>2</sub> Cost at Station (early market)</b>	On-site natural gas reformation <b>\$7.70 – \$10.30/kg</b>	On-site Electrolysis <b>\$10.00 – \$12.90/kg</b>	<b>\$3/gge</b>	--
<i>Average H<sub>2</sub> Fueling Rate</i>	0.77 kg/min		1.0 kg/min	0.65 kg/min

Outside of this project, DOE independent panels concluded at 500 replicate stations/year:

Distributed natural gas reformation at 1500 kg/day: **\$2.75-\$3.50/kg** (2006)

Distributed electrolysis at 1500kg/day: **\$4.90-\$5.70** (2009)



Outside  
review  
panel

# Future Work

- **Support DOE in launching new *vehicle* evaluation project**
  - “Light-Duty Fuel Cell Electric Vehicle Validation Data” (FOA 625)
- **Support DOE in launching new *infrastructure* evaluation project**
  - Transition H<sub>2</sub> station analysis activity to “Next Generation H2 Station Analysis” project led by Sam Sprik, initiated in January
  - Support DOE in launching new infrastructure validation project: “Validation of Hydrogen Refueling Station Performance” (FOA 626, topic 1)
- **Continue to leverage analysis capability to other validations**
- **Identify and exploit new opportunities to document FC & H2 progress publicly**

# Summary

**183 Vehicles:** 154,000 hours, 3.6M miles, 500K trips  
**25 Stations:** 152,000 kg produced/dispensed, 33K fuelings

- **Relevance**

- Provided DOE and taxpayers **strong return on investment** made in this 7-year project, the **largest** single FCEV & infrastructure demonstration in the world to date
- Many system-level DOE program targets validated by this project

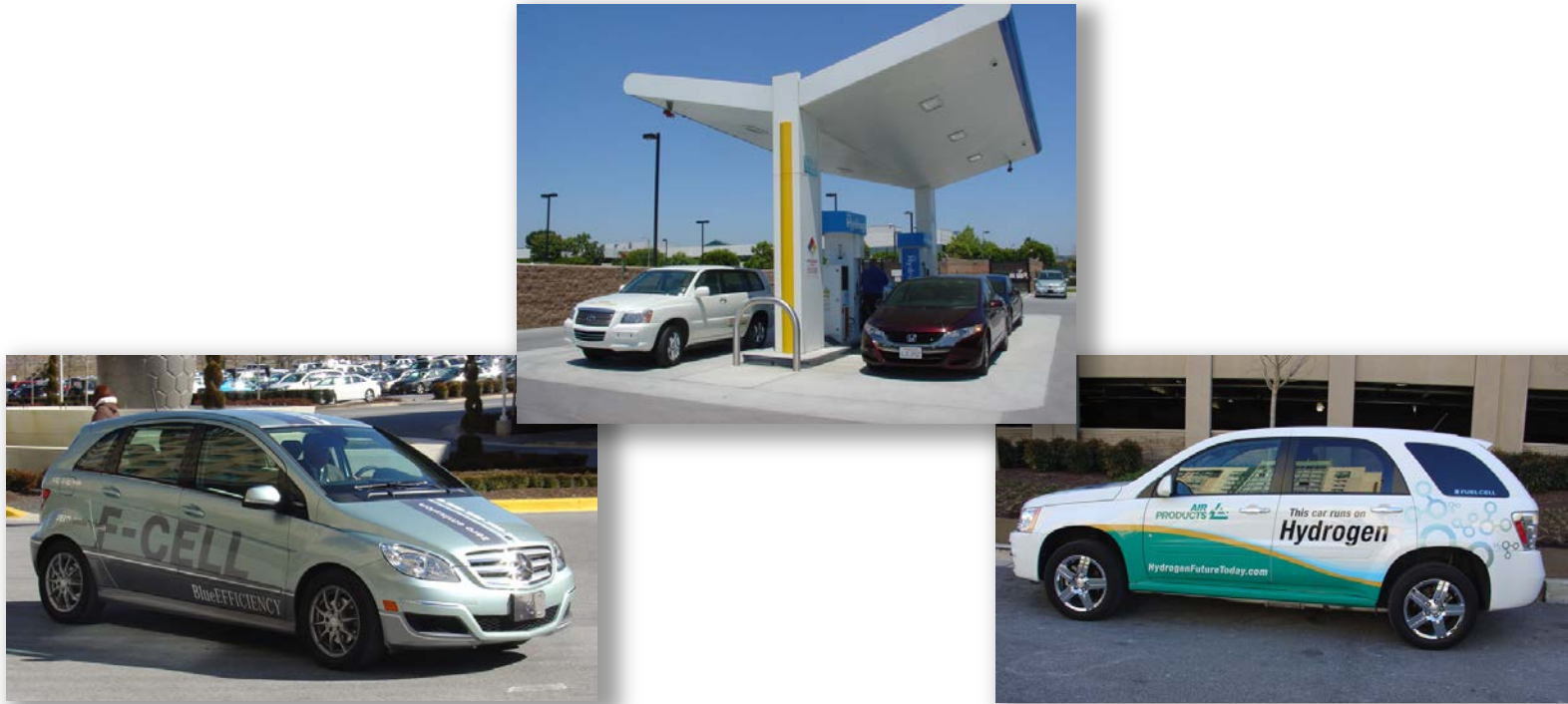
- **Approach**

- Collaborative relationship to analysis with **industry partners**
- Established core **HSDC and analysis capability** and tools
- This project is the 1st time such **comprehensive data** was collected by an independent 3rd-party and consolidated for public dissemination

- **Technical Accomplishments and Progress**

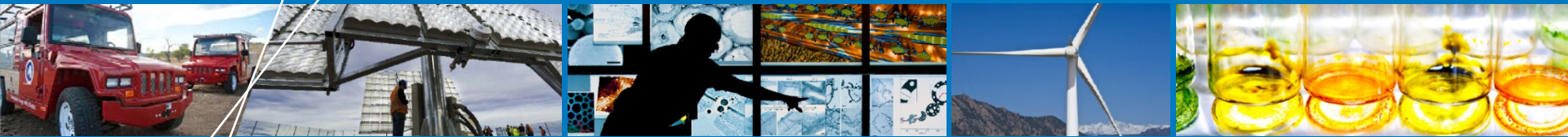
- **99 total CDP analysis results** available; published at conferences every 6 months
- Project **achieved the two key technical targets** on driving range (>250 miles) and FC durability (>2,000 hours) [refer to technical backup slides and Final Report]

# Questions and Discussion



Project Contact: Keith Wipke, National Renewable Energy Lab  
303.275.4451 [keith.wipke@nrel.gov](mailto:keith.wipke@nrel.gov)

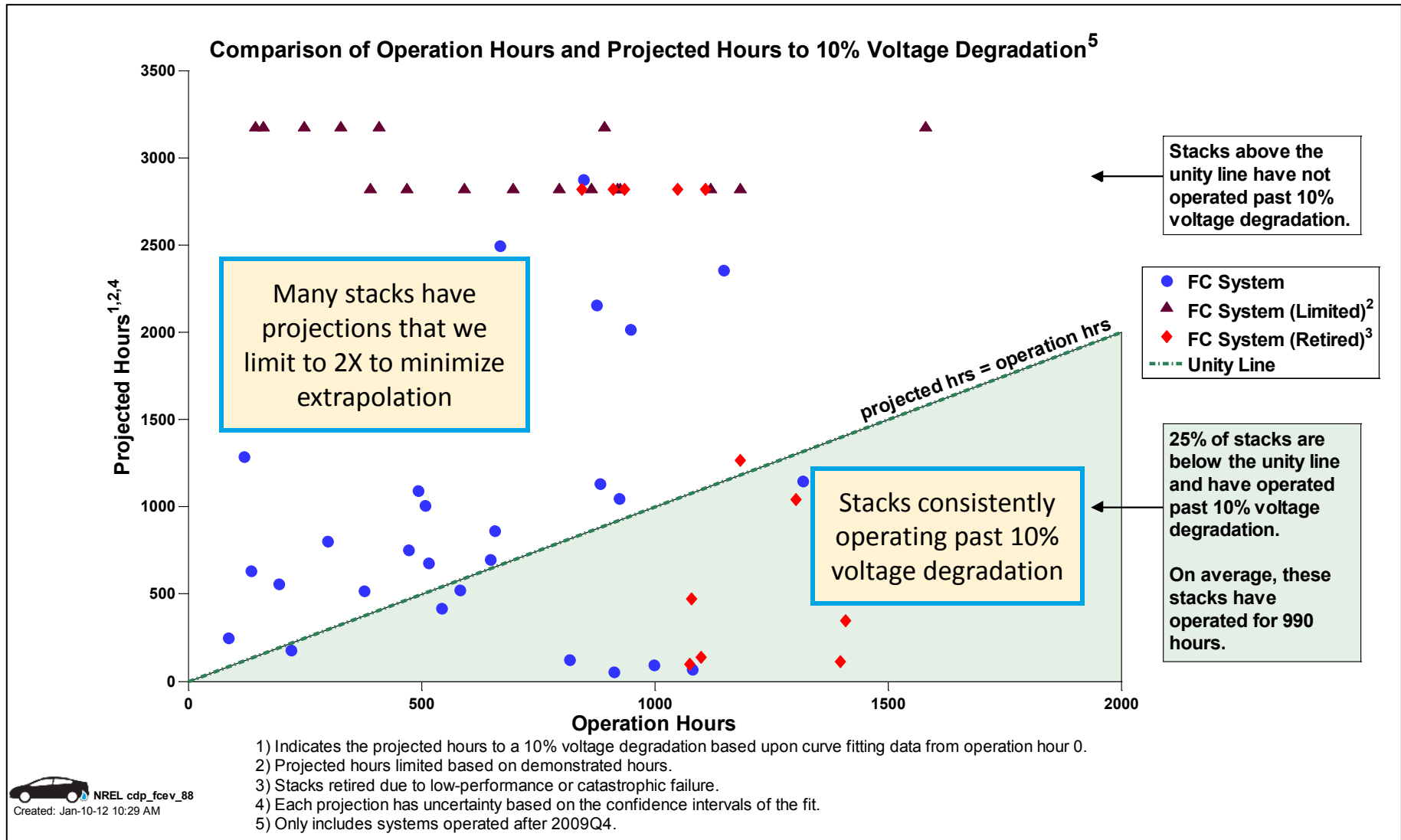
All public Learning Demo papers and presentations are available online at  
[http://www.nrel.gov/hydrogen/proj\\_tech\\_validation.html](http://www.nrel.gov/hydrogen/proj_tech_validation.html)



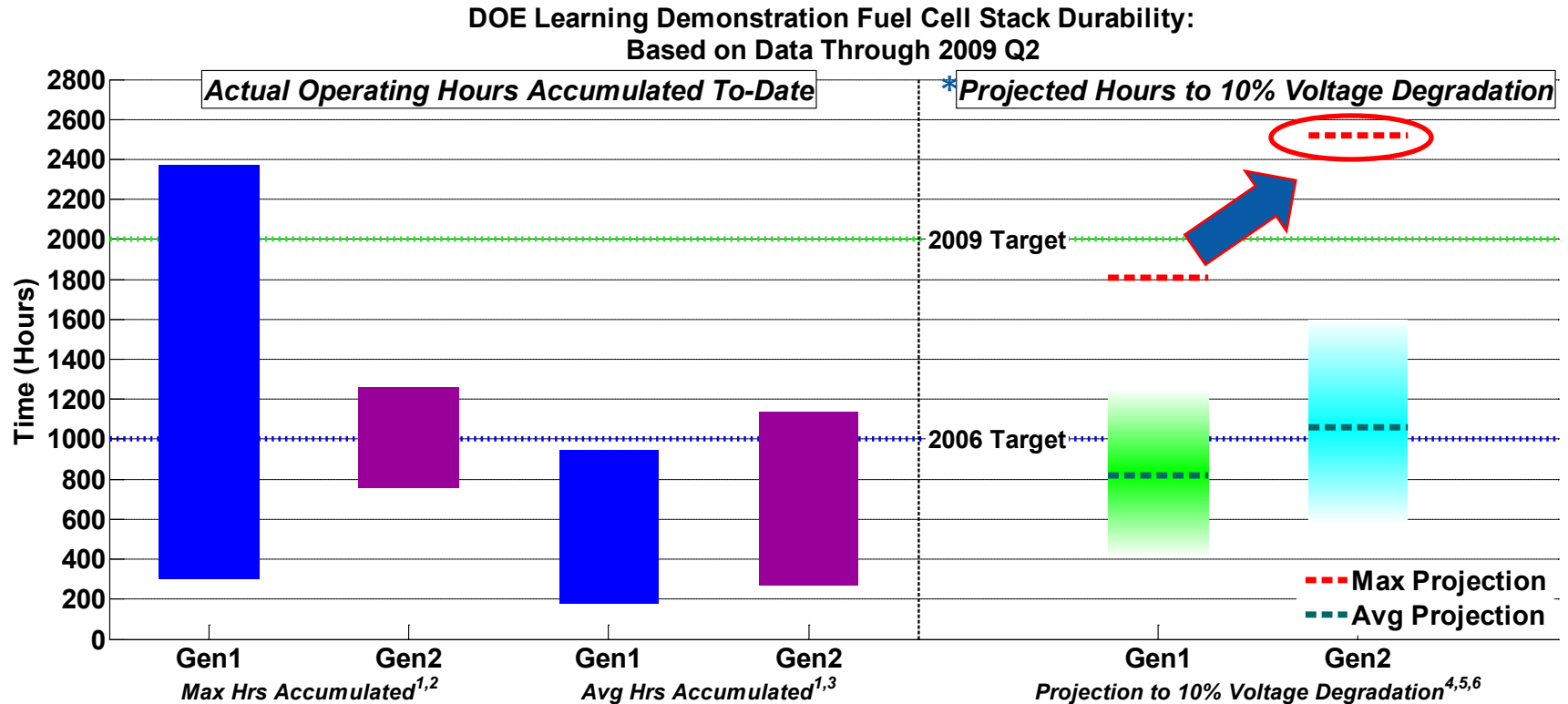
# Technical Backup Slides



# Accomplishment: Scatter Plot of Fuel Cell Operation Hours and Projected Hours to 10% Voltage Degradation

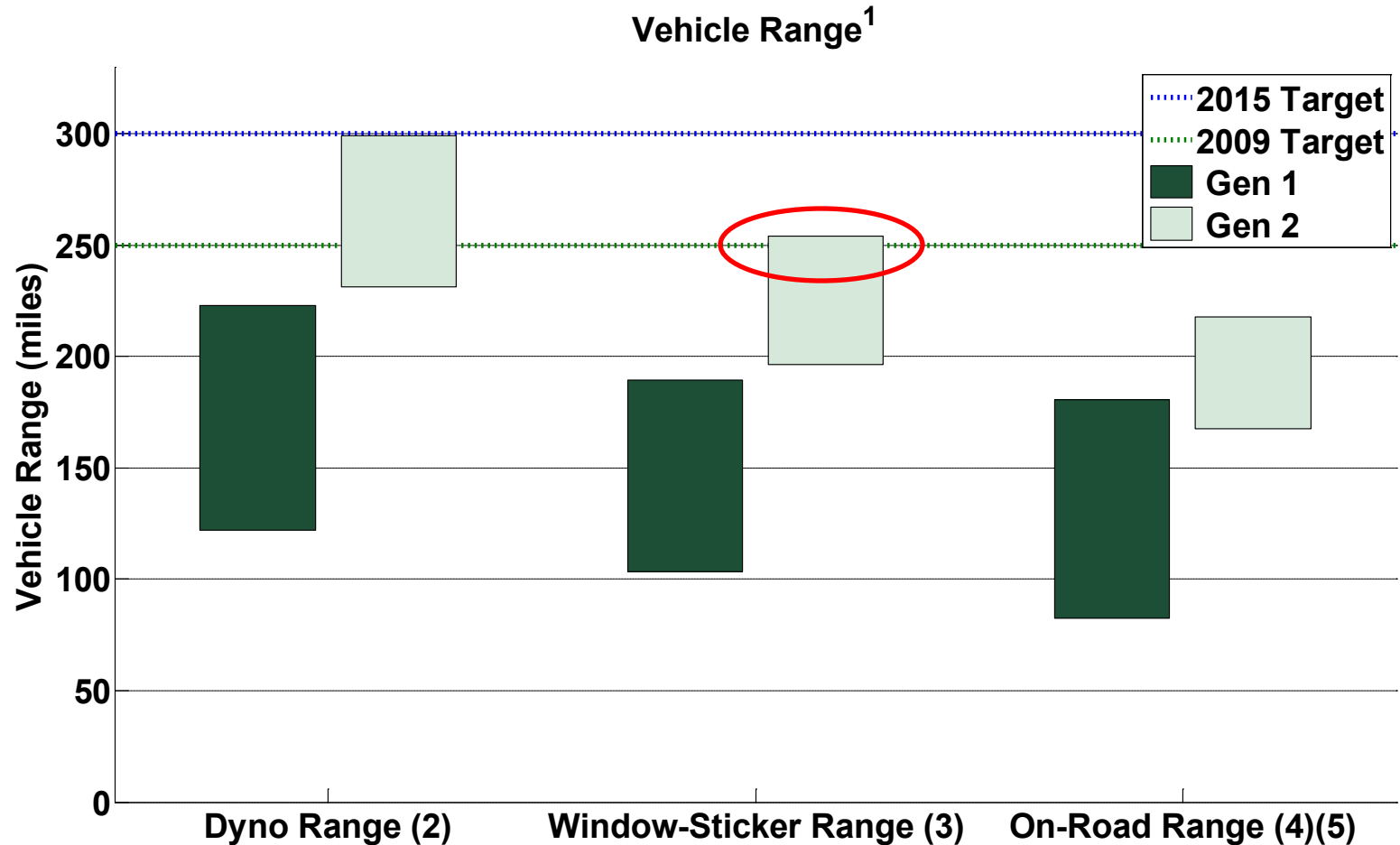


# 1) FC Durability Target of 2000 Hours Met By Gen 2 Projections (2010)



- (1) Range bars created using one data point for each OEM. Some stacks have accumulated hours beyond 10% voltage degradation.
- (2) Range (highest and lowest) of the maximum operating hours accumulated to-date of any OEM's individual stack in "real-world" operation.
- (3) Range (highest and lowest) of the average operating hours accumulated to-date of all stacks in each OEM's fleet.
- (4) Projection using on-road data – degradation calculated at high stack current. This criterion is used for assessing progress against DOE targets, may differ from OEM's end-of-life criterion, and does not address "catastrophic" failure modes, such as membrane failure.
- (5) Using one nominal projection per OEM: "Max Projection" = highest nominal projection, "Avg Projection" = average nominal projection. The shaded projection bars represents an engineering judgment of the uncertainty on the "Avg Projection" due to data and methodology limitations. Projections will change as additional data are accumulated.
- (6) Projection method was modified beginning with 2009 Q2 data, includes an upper projection limit based on demonstrated op hours.

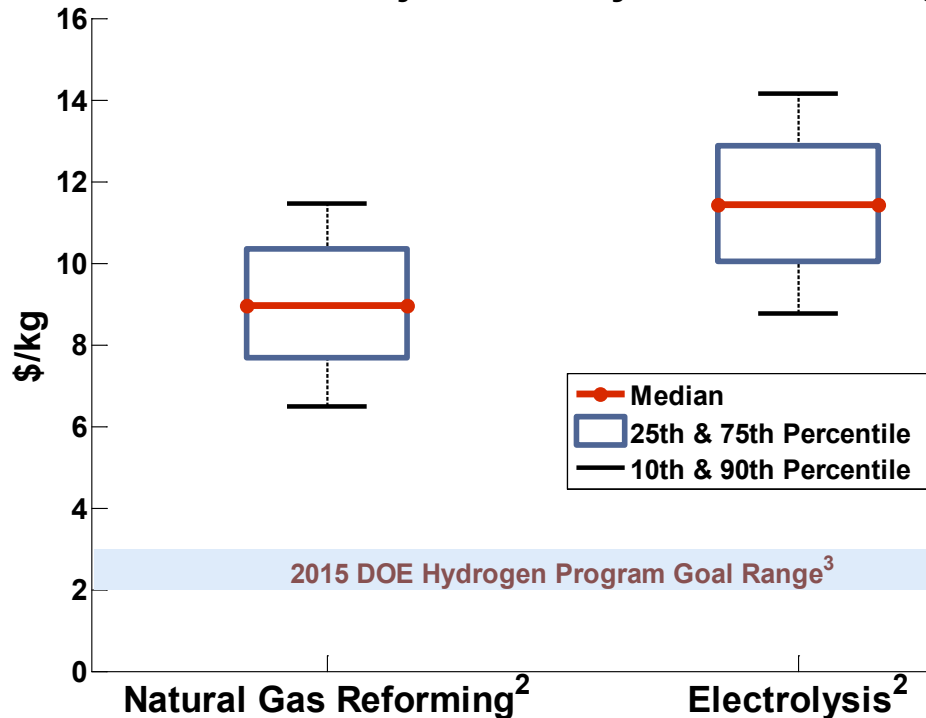
## 2) Vehicle Range Achieved 2009 Target of 250 Miles with Gen 2 Adjusted Fuel Economy (2010)



- (1) Range is based on fuel economy and usable hydrogen on-board the vehicle. One data point for each make/model.  
(2) Fuel economy from unadjusted combined City/Hwy per DRAFT SAE J2572.  
(3) Fuel economy from EPA Adjusted combined City/Hwy ( $0.78 \times \text{Hwy}$ ,  $0.9 \times \text{City}$ ).  
(4) Excludes trips < 1 mile. One data point for on-road fleet average of each make/model.  
(5) Fuel economy calculated from on-road fuel cell stack current or mass flow readings.

### 3) Projected Early Market H<sub>2</sub> Production Cost from Learning Demo Energy Partners' Inputs (2010)

Projected Early Market 1500 kg/day Hydrogen Cost<sup>1</sup> \*



#### Key H<sub>2</sub> Cost Elements and Ranges

Input Parameter	Minimum (P10)	Maximum (P90)
Facility Direct Capital Cost	\$10M	\$25M
Facility Capacity Utilization	85%	95%
Annual Maintenance & Repairs	\$150K	\$600K
Annual Other O&M	\$100K	\$200K
Annual Facility Land Rent	\$50K	\$200K
Natural Gas Prod. Efficiency (LHV)	65%	75%
Electrolysis Prod. Efficiency (LHV)	35%	62%

This project provides an excellent learning opportunity, but stations were not meant to emulate high volume replicate stations of the future. Permitting was in transition.

(1) Reported hydrogen costs are based on estimates of key cost elements from Learning Demonstration energy company partners and represent the cost of producing hydrogen on-site at the fueling station, using either natural gas reformation or water electrolysis, dispensed to the vehicle. Costs reflect an assessment of hydrogen production technologies, not an assessment of hydrogen market demand.

(2) Hydrogen production costs for 1500 kg/day stations developed using DOE's H<sub>2</sub>A Production model, version 2.1. Cost modeling represents the lifetime cost of producing hydrogen at fueling stations installed during an early market rollout of hydrogen infrastructure and are not reflective of the costs that might be seen in a fully mature market for hydrogen installations. Modeling uses default H<sub>2</sub>A Production model inputs supplemented with feedback from Learning Demonstration energy company partners, based on their experience operating on-site hydrogen production stations. H<sub>2</sub>A-based Monte Carlo simulations (2,000 trials) were completed for both natural gas reforming and electrolysis stations using default H<sub>2</sub>A values and 10th percentile to 90th percentile estimated ranges for key cost parameters as shown in the table. Capacity utilization range is based on the capabilities of the production technologies and could be significantly lower if there is inadequate demand for hydrogen.

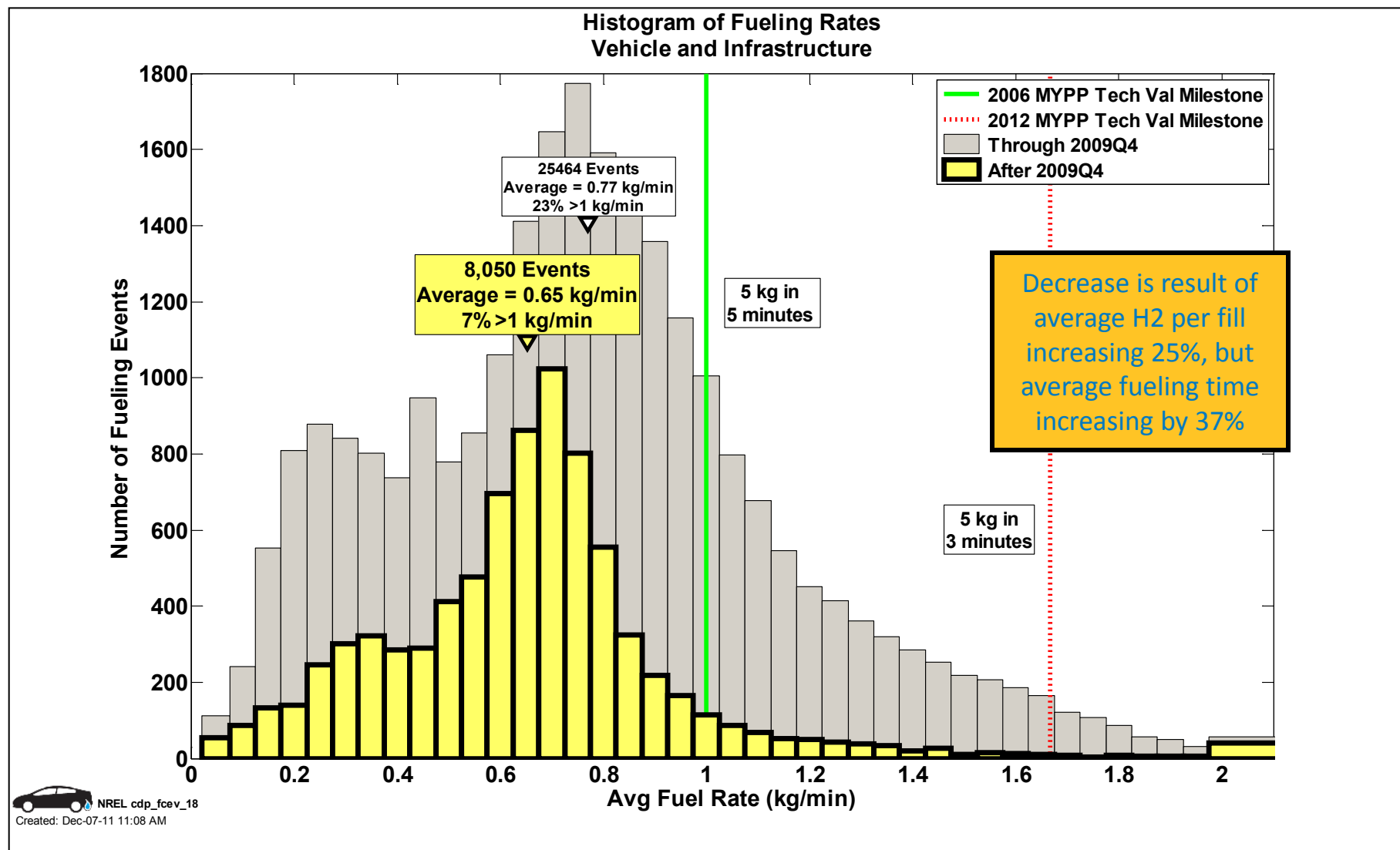
(3) DOE has a hydrogen cost goal of \$2-\$3/kg for future (2015) 1500 kg/day hydrogen production stations installed at a rate of 500 stations per year.

Outside of this project, DOE independent panels concluded at 500 replicate stations/year:

Distributed natural gas reformation at 1500 kg/day: **\$2.75-\$3.50/kg** (2006)

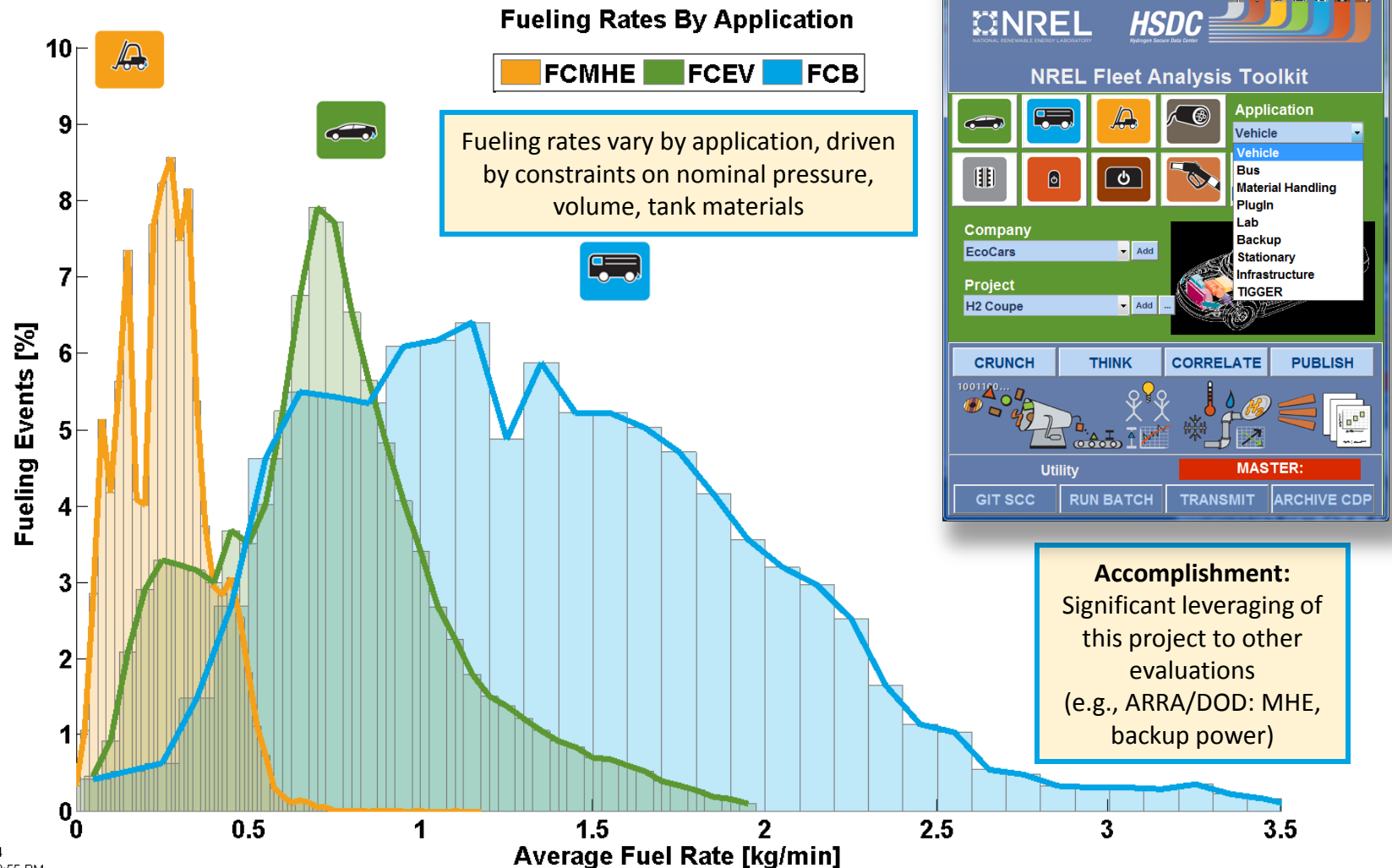
Distributed electrolysis at 1500kg/day: **\$4.90-\$5.70** (2009)

# Average Fueling Rate Decreased 16% Due to Some High Throughput Stations Leaving Project

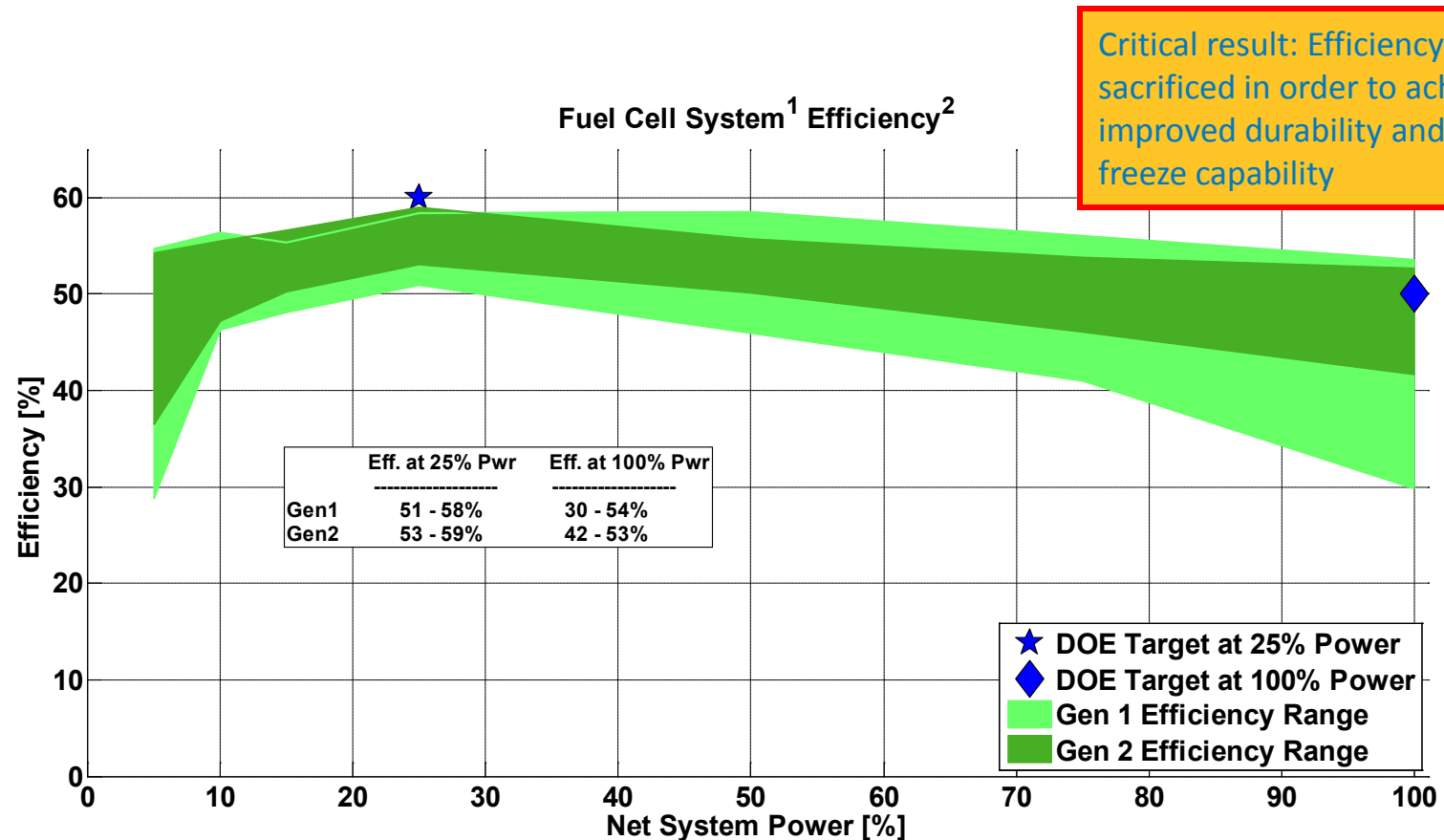




# FUELING: Leveraged Effort to Other Fuel Cell Applications; Cross-Application CDPs Expanding



# EFFICIENCY: Verified High Gen 2 Fuel Cell System Efficiency Maintained (Compared to Gen 1)

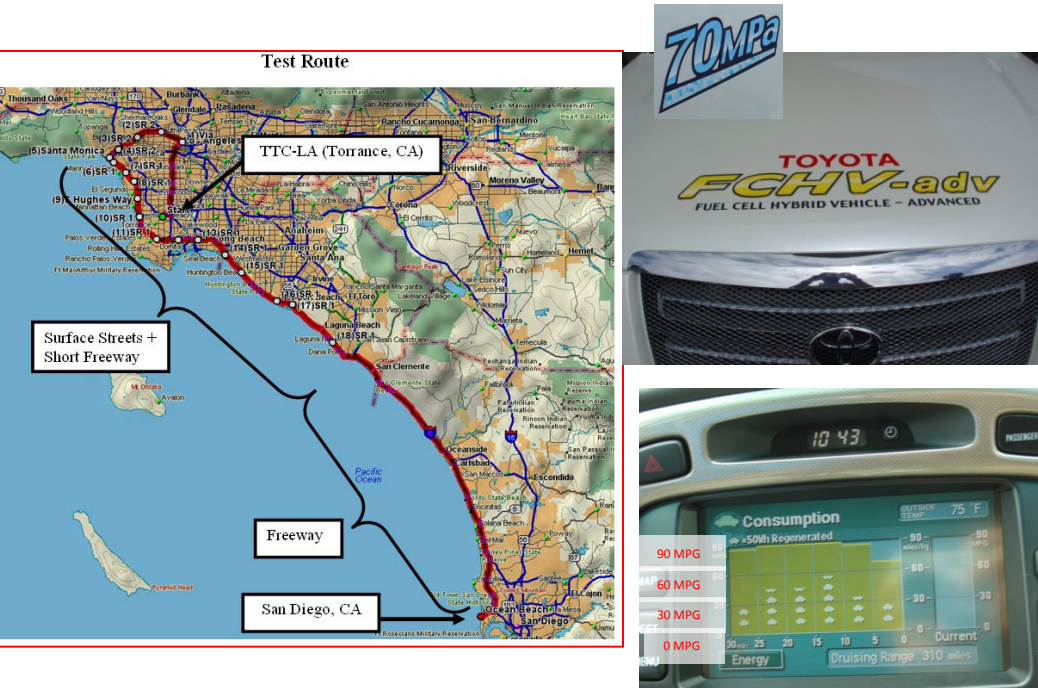


<sup>1</sup> Gross stack power minus fuel cell system auxiliaries, per DRAFT SAE J2615. Excludes power electronics and electric drive.

<sup>2</sup> Ratio of DC output energy to the lower heating value of the input fuel (hydrogen).

<sup>3</sup> Individual test data linearly interpolated at 5,10,15,25,50,75, and 100% of max net power. Values at high power linearly extrapolated due to steady state dynamometer cooling limitations.

# RANGE: NREL/SRNL Experiment Verified Toyota FCHV-adv Capable of up to 430-Mile Driving Range Without Refueling on June 30, 2009



	Average trip distance (miles)	H <sub>2</sub> consumed (kg)	Remaining usable H <sub>2</sub> (kg)	Calculated remaining range (miles)	(miles)	(miles)
Vehicle #1	331.50	4.8255	1.4854	102.04	433.55	431
Vehicle #2	331.45	4.8751	1.4328	97.41	428.87	

Toyota video: <http://www.youtube.com/watch?v=iz0vD5E7gIA>

Report: [http://www.nrel.gov/hydrogen/pdfs/toyota\\_fchv-adv\\_range\\_verification.pdf](http://www.nrel.gov/hydrogen/pdfs/toyota_fchv-adv_range_verification.pdf)

SRNS-STI-2009-00446

Evaluation of Range Estimates for Toyota FCHV-adv Under Open Road Driving Conditions

Keith Wipke<sup>1</sup>, Donald Anton<sup>2</sup>, Sam Sprik<sup>1</sup>

August 10, 2009  
PTS-05 of SRNS CRADA No. CR-04-003

SRNL

Savannah River National Laboratory

NREL

National Renewable Energy Laboratory

Innovation for Our Energy Future

<sup>1</sup> National Renewable Energy Laboratory

<sup>2</sup> Savannah River National Laboratory

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