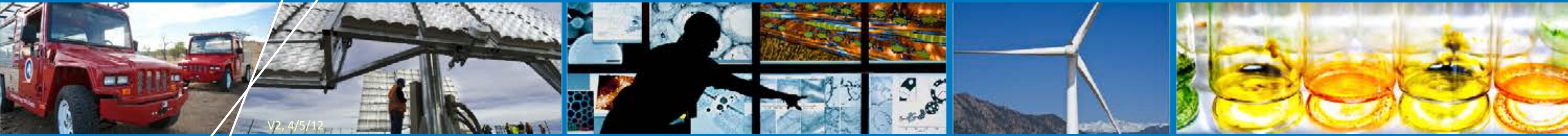
Project ID# TV001

Controlled Hydrogen Fleet and Infrastructure Analysis



2012 DOE Annual Merit Review and Peer Evaluation Meeting

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

May 17, 2012: Washington, DC

NREL/PR-5600-54475

Fuel Cell Electric Vehicle Learning Demo Project Objectives, Relevance, and Targets

- **Objectives**
  - Validate H_2 FC Vehicles and Infrastructure in Real-World Setting
  - Identify Current Status and Evolution of the Technology
- **Relevance**
  - Objectively Assess Progress Toward Targets and Market Needs
  - Provide Feedback to H_2 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 (Outside review panel)	$2-4/gge**

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

APC/Shell Pipeline station, Torrance, CA. Photo: NREL

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

Project Overview

Timeline

- **Project start: FY03**
- **Project end: FY12**
- **98% of Task III complete (see timeline slide)**

Budget

- Funding prior to FY11 : $5517K
- FY11 funding: $650K
- **Planned FY12 funding: $400K**

($6,567K total over 10 fiscal years)*

Partners

- See partner slide

Tech. Val. Barriers

A. **Vehicles** – lack of controlled & on-road H_2 vehicle and FC system data

B. **Storage** – technology does not yet provide necessary 300+ mile range

C. **Hydrogen Refueling Infrastructure** – cost and availability

D. **Maintenance and Training Facilities** – lack of facilities and trained personnel

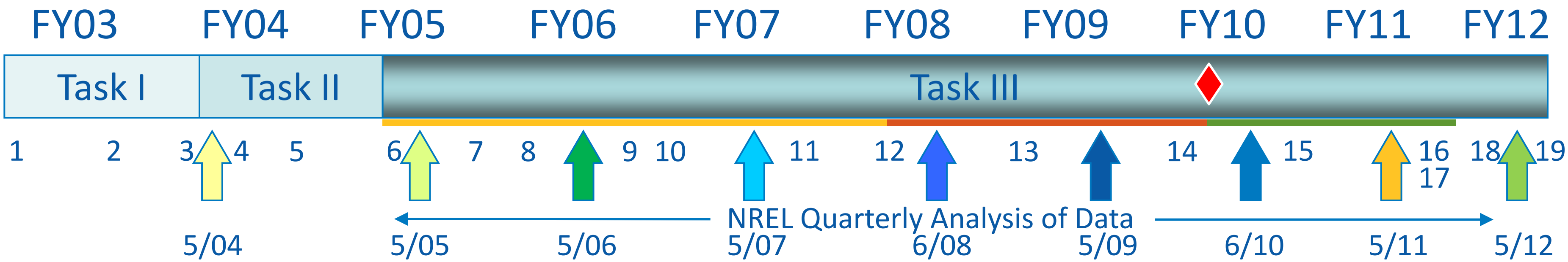
E. **Codes and Standards** – lack of adoption/validation

H. **Hydrogen Production from Renewables** – need for cost, durability, efficiency data for vehicular application

I. **H_2 and Electricity Co-Production** – cost and durability

*Related OEM/energy Learning Demonstration projects received $170M DOE funding and provided $189M cost-share for a total of $359M

Approach and Accomplishments: Project Timeline and Major Milestones



2 teams concluded their projects

Task I – Project Preparation [100% Complete]

Task II – Project Launch [100% Complete]

Task III – Data Analysis and Feedback to R&D activities (partial list) [98% Complete]

Gen 1
- 8 Publication of first "composite data products"
- 9 Evaluate FC stack time to 10% voltage degradation relative to 1000-hour target
- 10 Decision for purchase of additional vehicles based on performance, durability, cost
- 11 Preliminary evaluation of dominant real-world factors influencing FC degradation

Gen 1 + Gen 2
- 12 Introduction of 2nd generation FC systems into vehicles begins
- 13 FCVs demonstrate **250-mile range** without impacting passenger cargo compartment
- 14 Validate FCVs with **2,000 hour durability** and **$3.00/gge** (based on volume production)

2 OEMs
- 15 Data analysis continues with data from 2 of the 4 OEM/Energy teams plus CHIP stations
- 16 Conclusion of data submission to NREL on pre-commercial FCEVs (Sept. 2011)
- 17 DOE Milestone: Validate 40 adv. technology FCEVs with up to 600 hours operation
- 18 **Final data analysis and report** on Learning Demonstration
- 19 Preparation for next FCEV validation project

Project Approach

- **Provide facility and staff for securing and analyzing industry sensitive data**
  - NREL Hydrogen Secure Data Center (HSDC)
- **Perform analysis using detailed data in HSDC to:**
  - Evaluate current status and progress toward targets
  - Feed back current technical challenges and opportunities into DOE H_2 R&D program
  - Provide originating companies with analytical results on their own data (detailed data products)
  - Collaborate with industry partners on new analyses

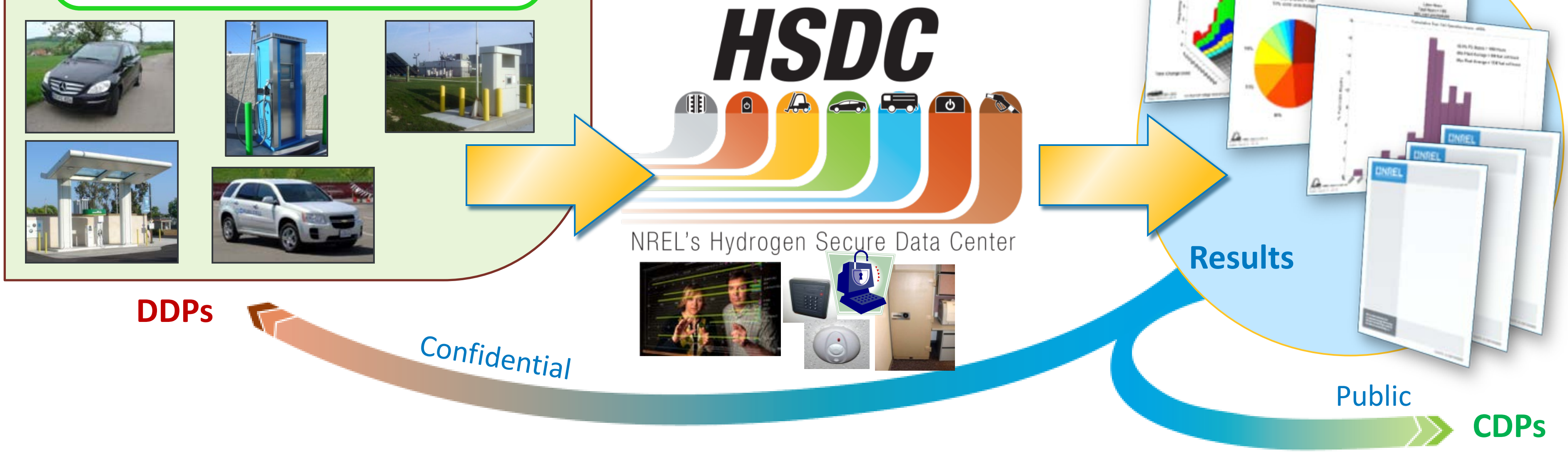
- **Publish/present progress of project to public and stakeholders (composite data products)**

Project Approach (cont.)

Supporting Both DOE/Public as Well as Technology Developers

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

Internal analysis completed quarterly



Detailed Data Products (DDPs)

- Individual data analyses
- Identify individual contribution to CDPs
- Shared every six months only with the partner who supplied the data[1]

Composite Data Products (CDPs)

- Aggregated data across multiple systems, sites, and teams
- Publish analysis results every six months without revealing proprietary data[2]

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)

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

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

DAIMLER

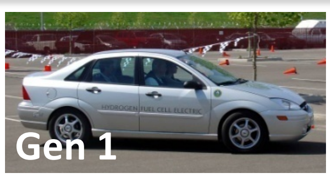
GM

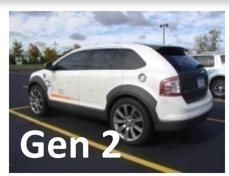
AIR PRODUCTS (CHIP)*

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

Ford

bp





Chevron

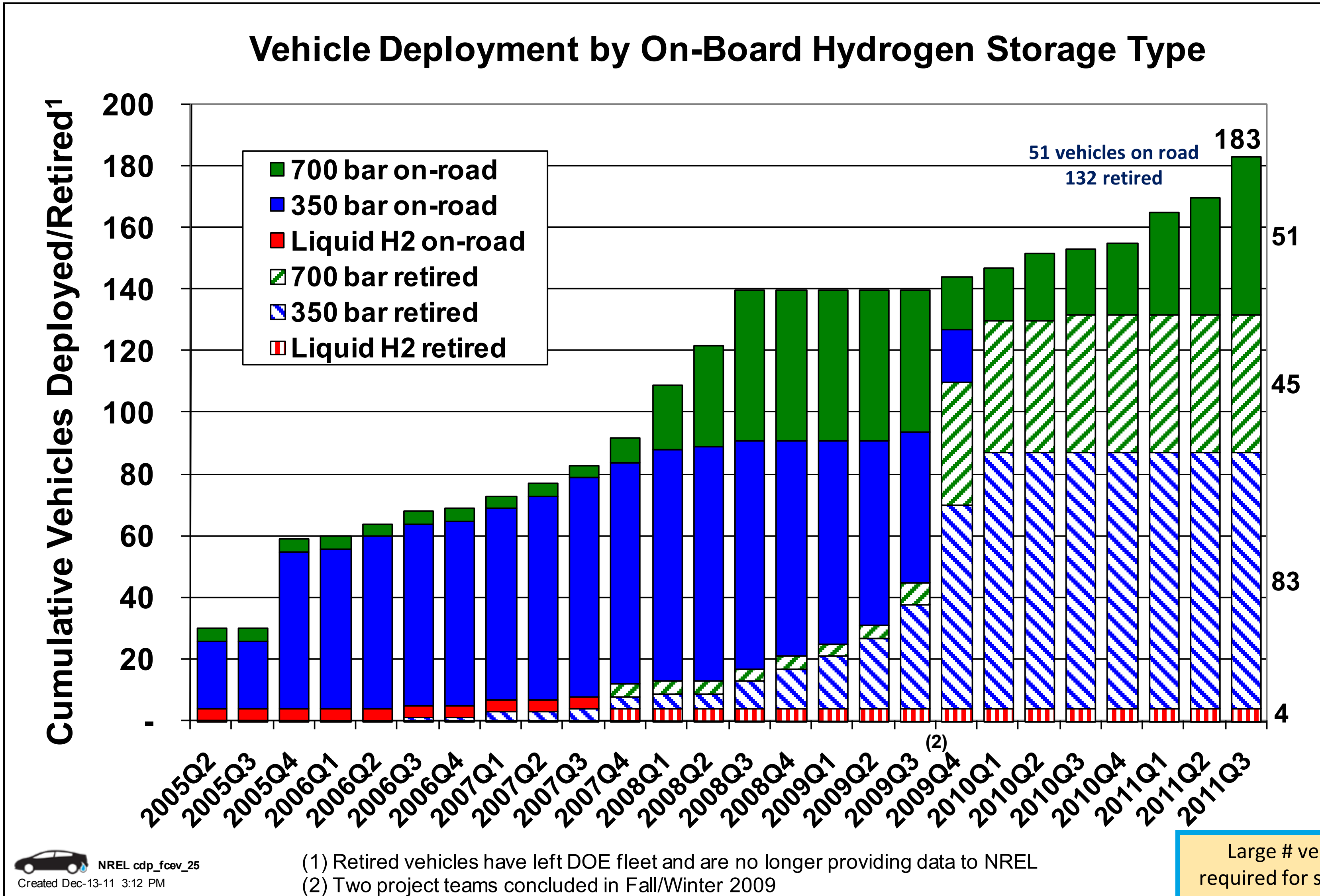
UTC Power
A United Technologies Company

HYUNDAI

KIA

*CHIP = California Hydrogen Infrastructure Project

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

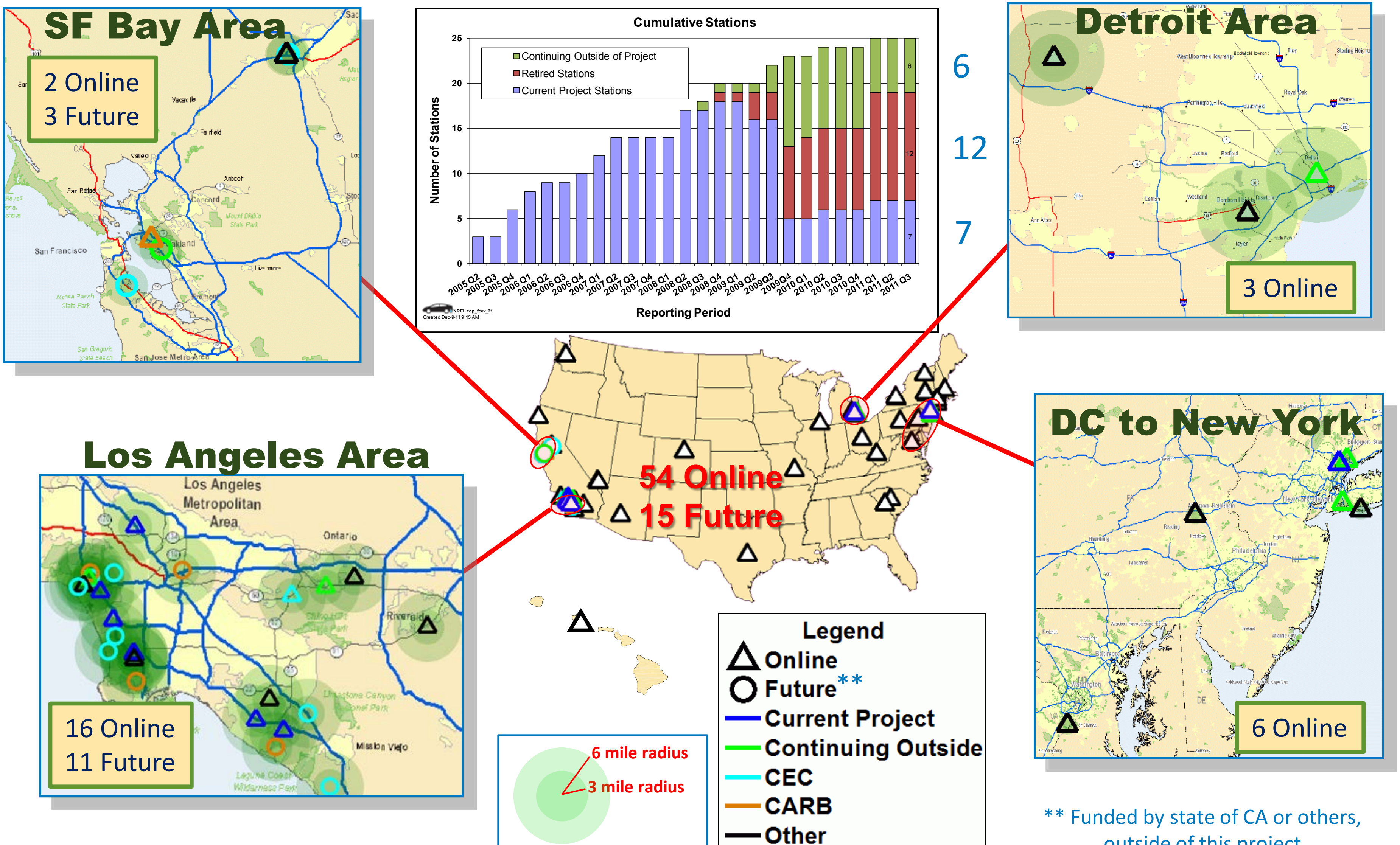


(1) Retired vehicles have left DOE fleet and are no longer providing data to NREL
(2) Two project teams concluded in Fall/Winter 2009

Large # vehicles required for statistical significance

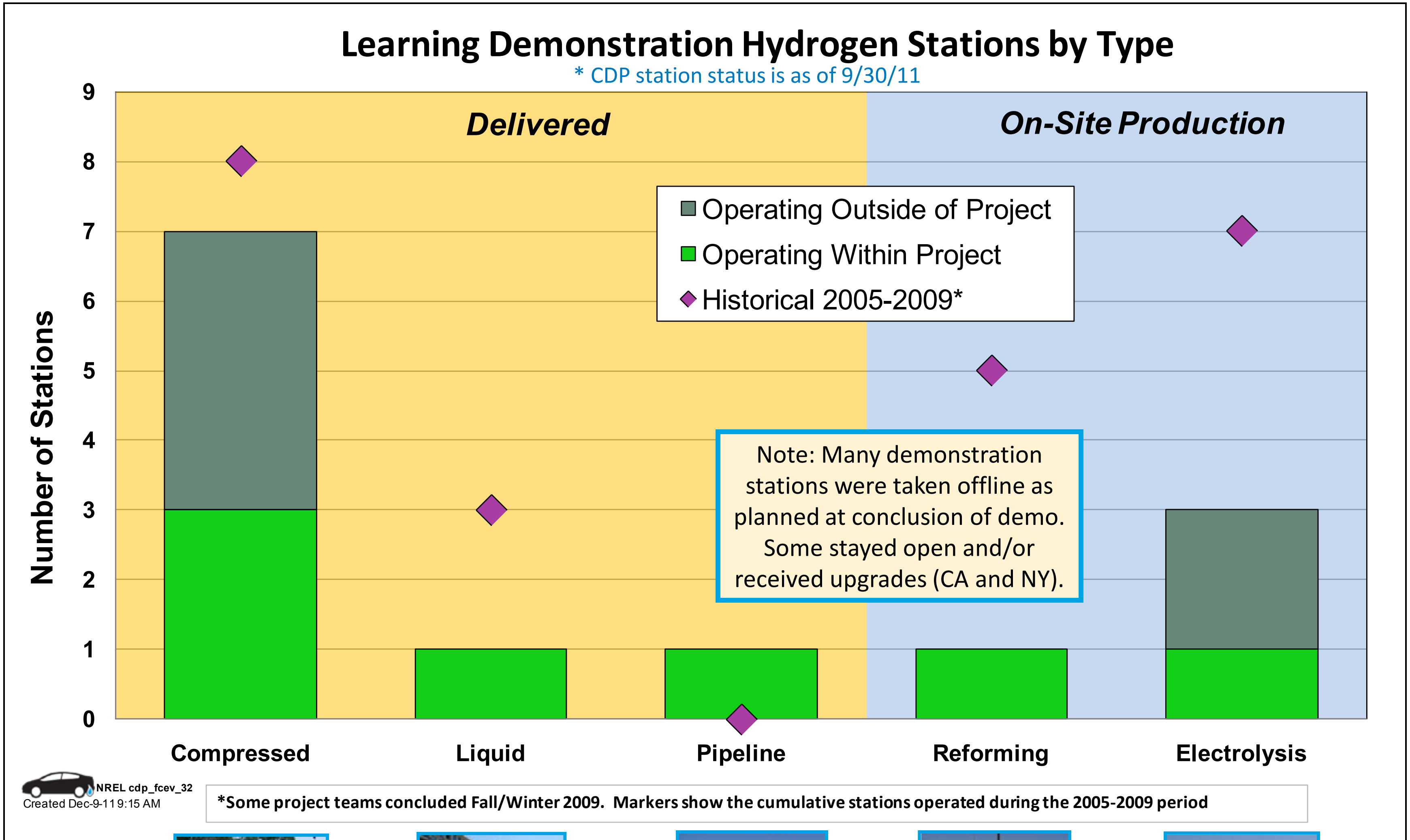
Infrastructure Status: Out of 25 Project Stations, 13 Are Still Operational* (6 outside of DOE project)

* CDP station status is as of 9/30/11



** Funded by state of CA or others, outside of this project

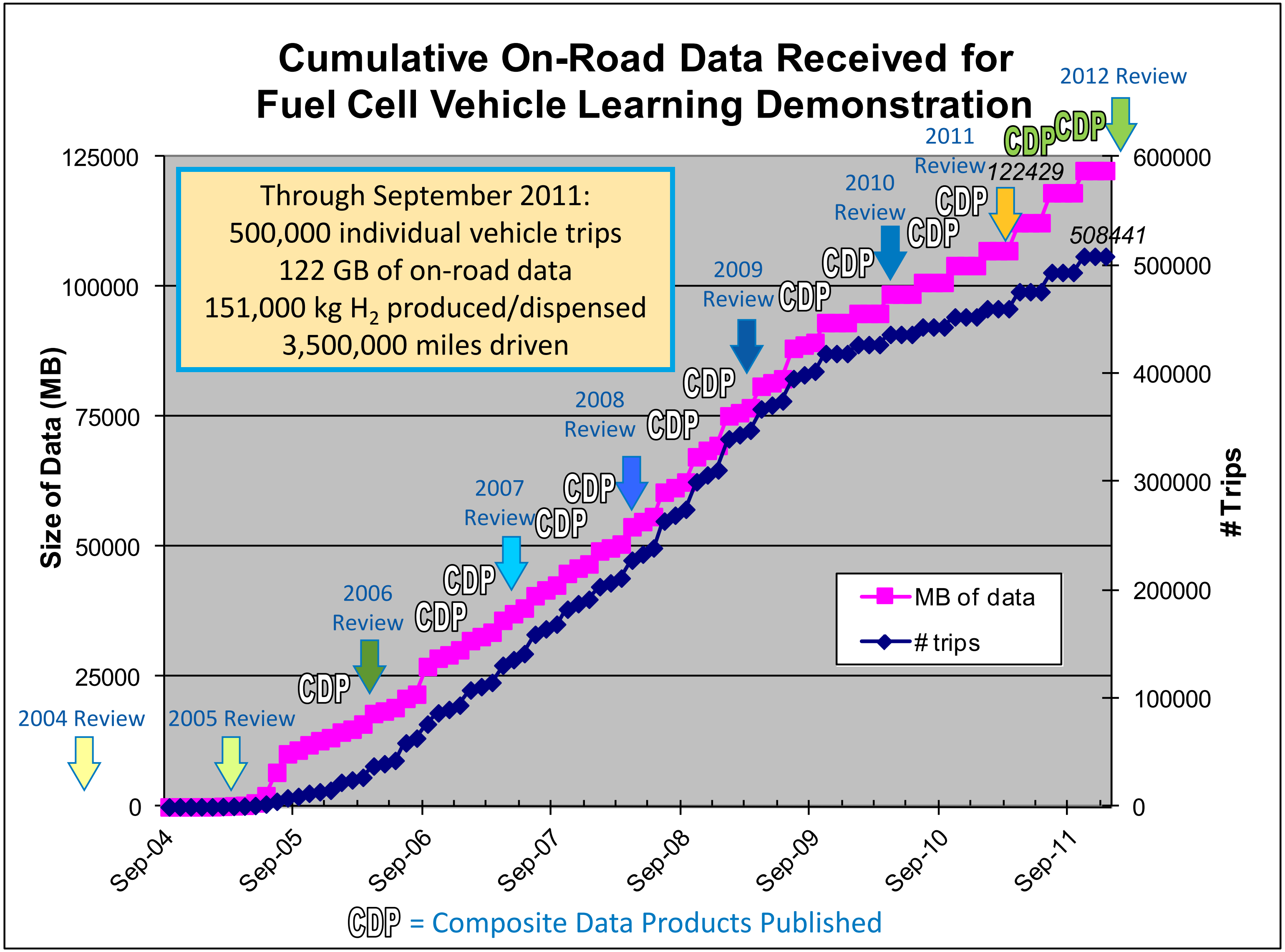
Accomplishment: Project Evaluated Many Types of Hydrogen Stations and Made Results Public





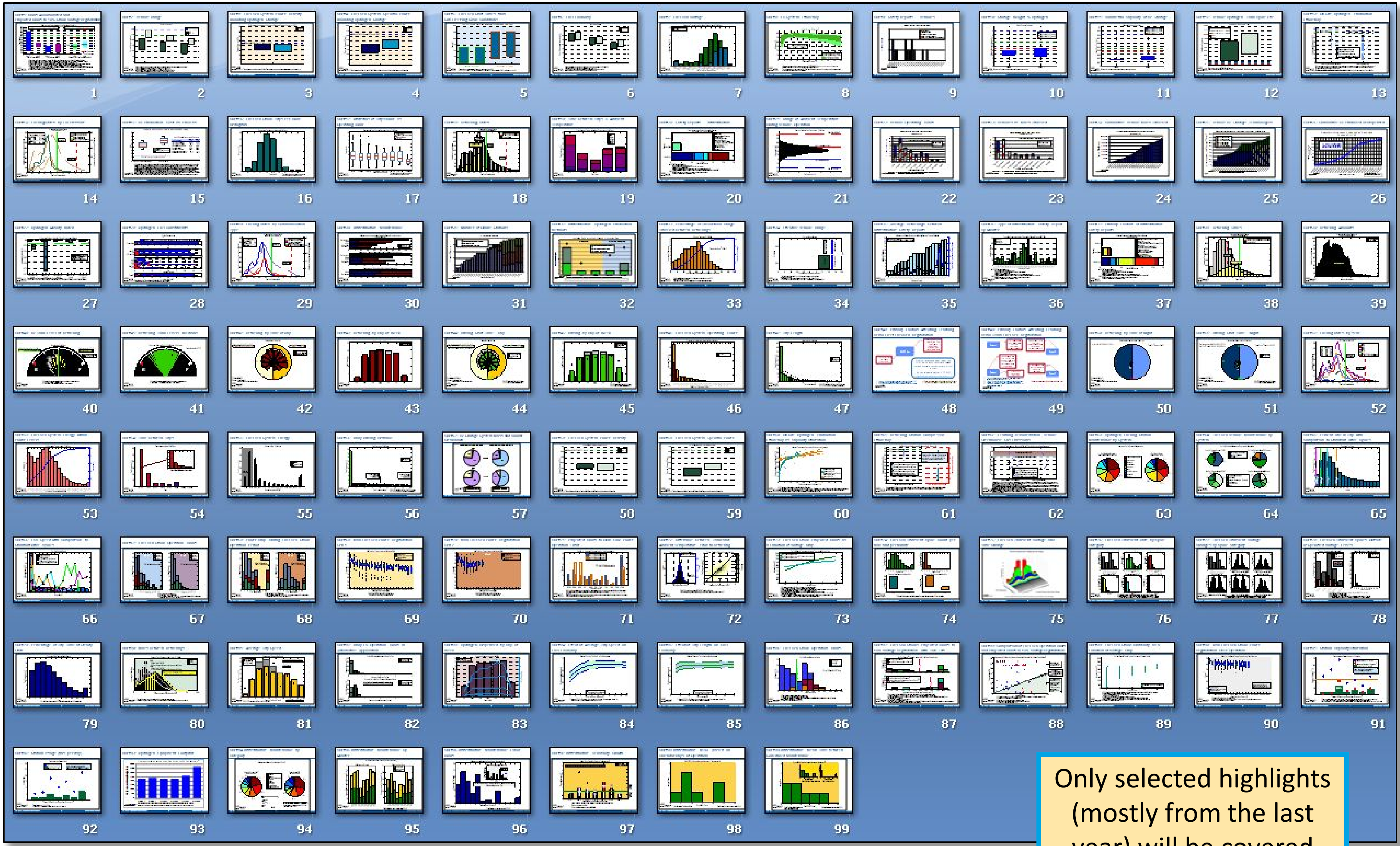


Accomplishment: 27 Quarters (7 years) of Data Analyzed to Date, Two New Sets of Composite Data Products Published Since Last AMR



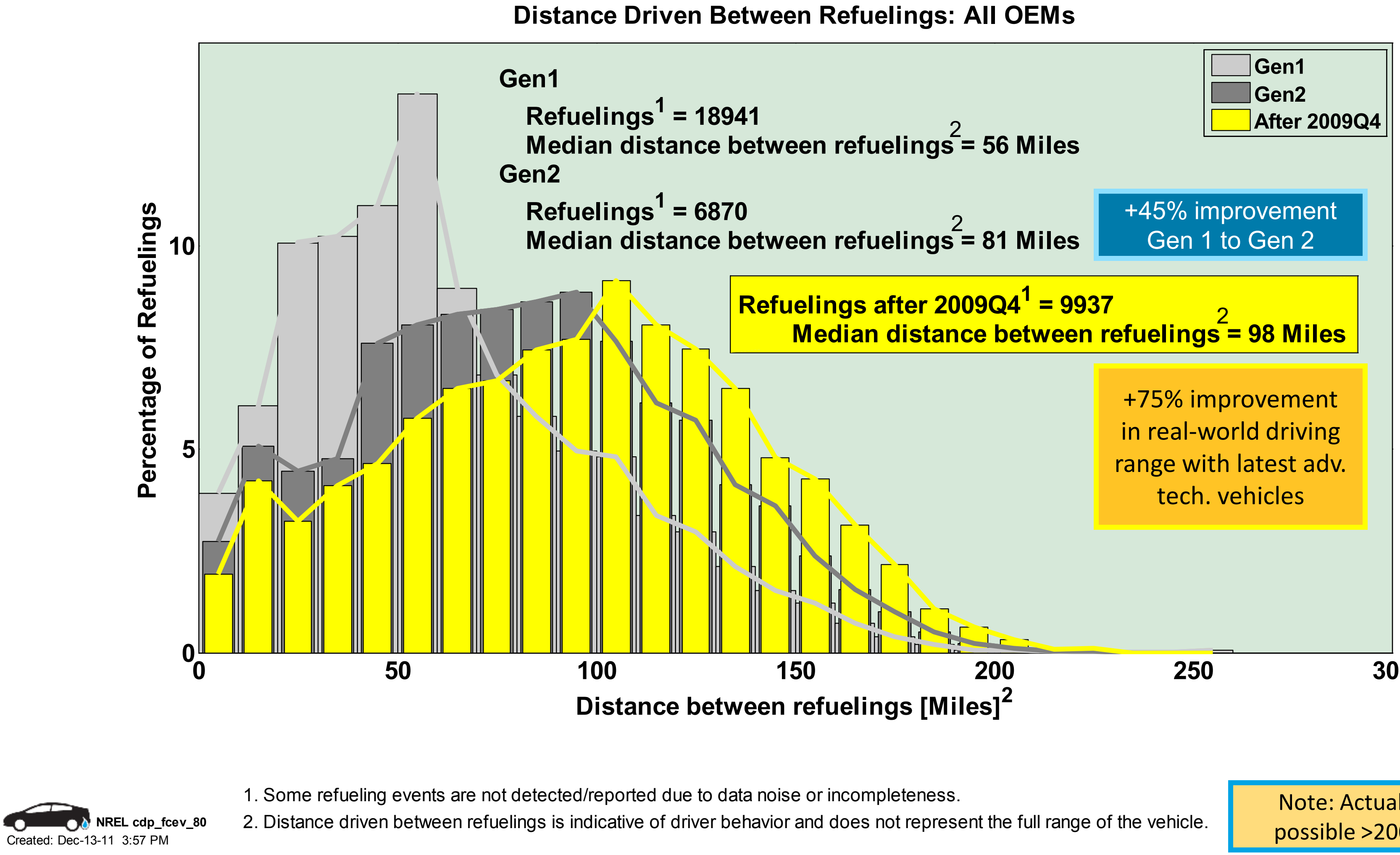
CDP = Composite Data Products Published

Accomplishment: Total of 99 CDPs Published (40 Winter 2011 CDPs)



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

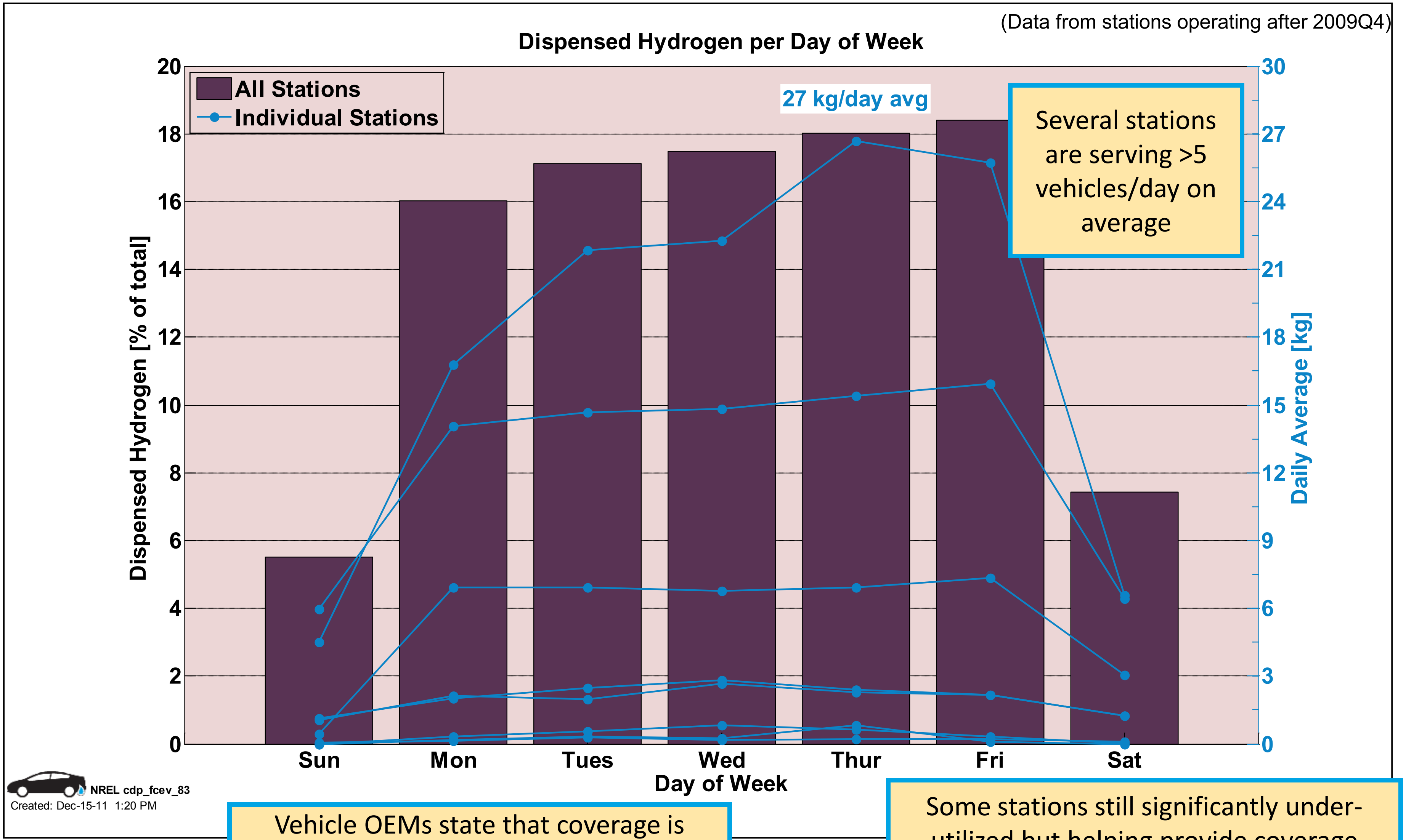
Accomplishment: Vehicles Show Continued Improvement in Real-World Driving Range



1. Some refueling events are not detected/reported due to data noise or incompleteness.
2. Distance driven between refuelings is indicative of driver behavior and does not represent the full range of the vehicle.

Note: Actual range possible >200 miles

Accomplishment: New Infrastructure CDP Gives Insight Into Specific Fueling Usage Patterns

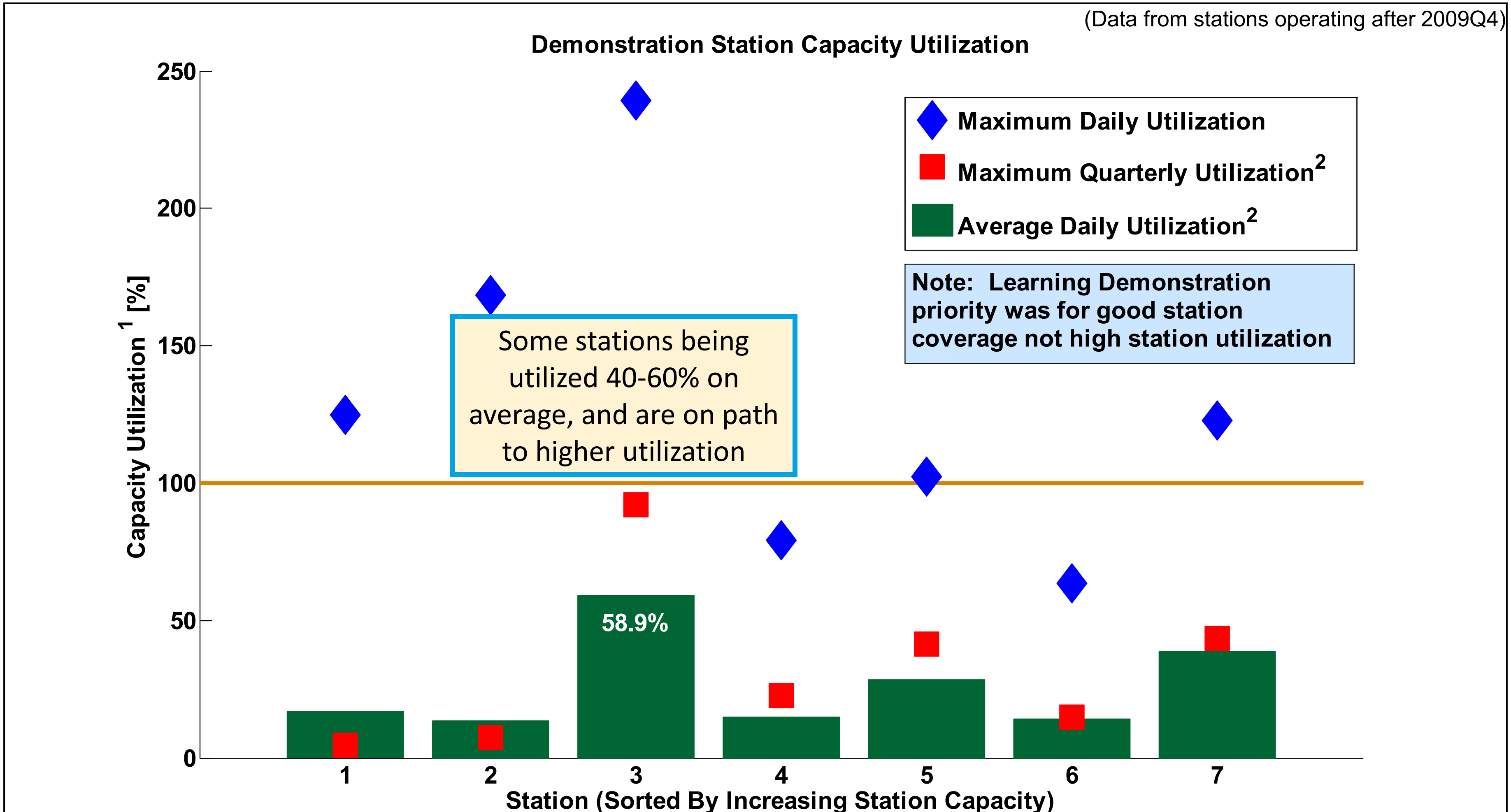


Several stations are serving >5 vehicles/day on average

Vehicle OEMs state that coverage is more important right now than capacity

Some stations still significantly under-utilized but helping provide coverage

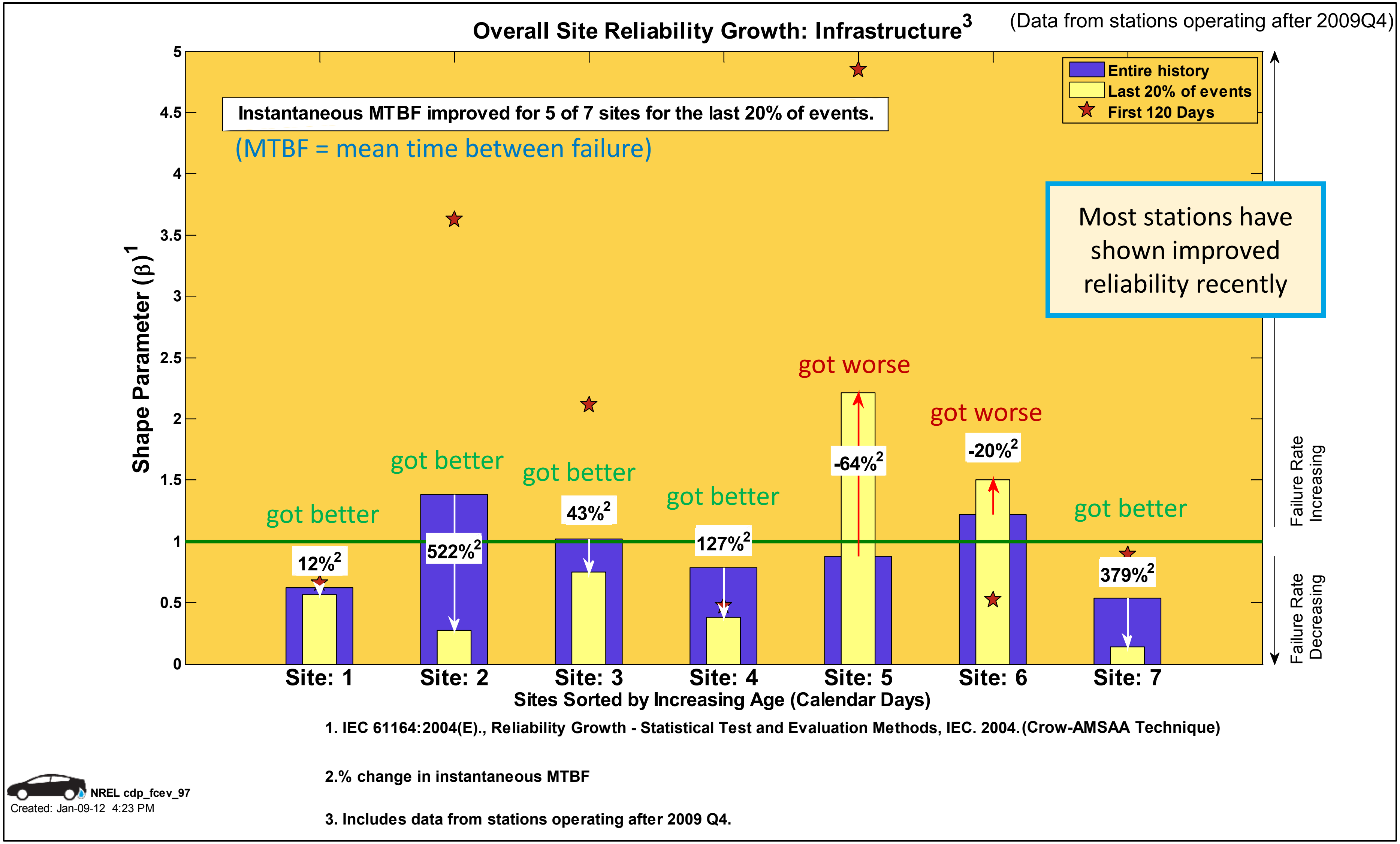
Accomplishment: While Station Focus is on Coverage, We've Tracked Capacity Usage as Baseline for Future



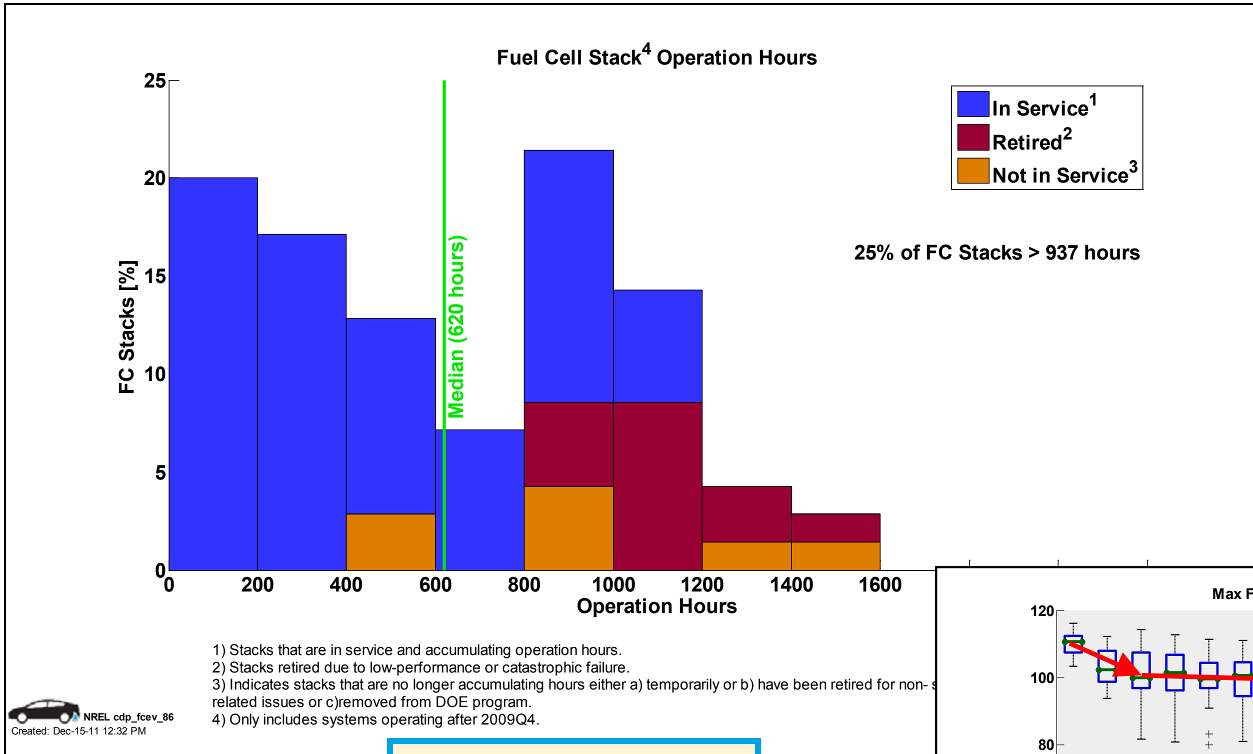
[1] Station nameplate capacity reflects a variety of system design consderations including system capacity, throughput, system reliability and durability, and maintenance. Actual daily usage may exceed nameplate capacity.

[2] Maximum quarterly utilization considers all days; average daily utilization considers only days when at least one filling occurred

Accomplishment: Instantaneous MTBF Improved for 5 of the 7 Sites for the Last 20% of Maintenance Events

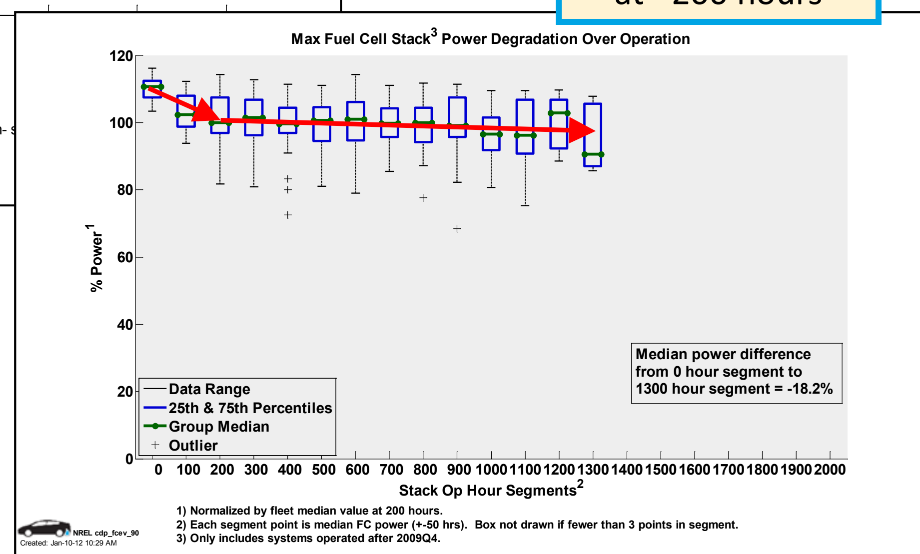


Accomplishment: Evaluated FC Durability Data from FCEVs After 2009Q4 – Fuel Cell Stack Operation Hours and Max Power Degradation

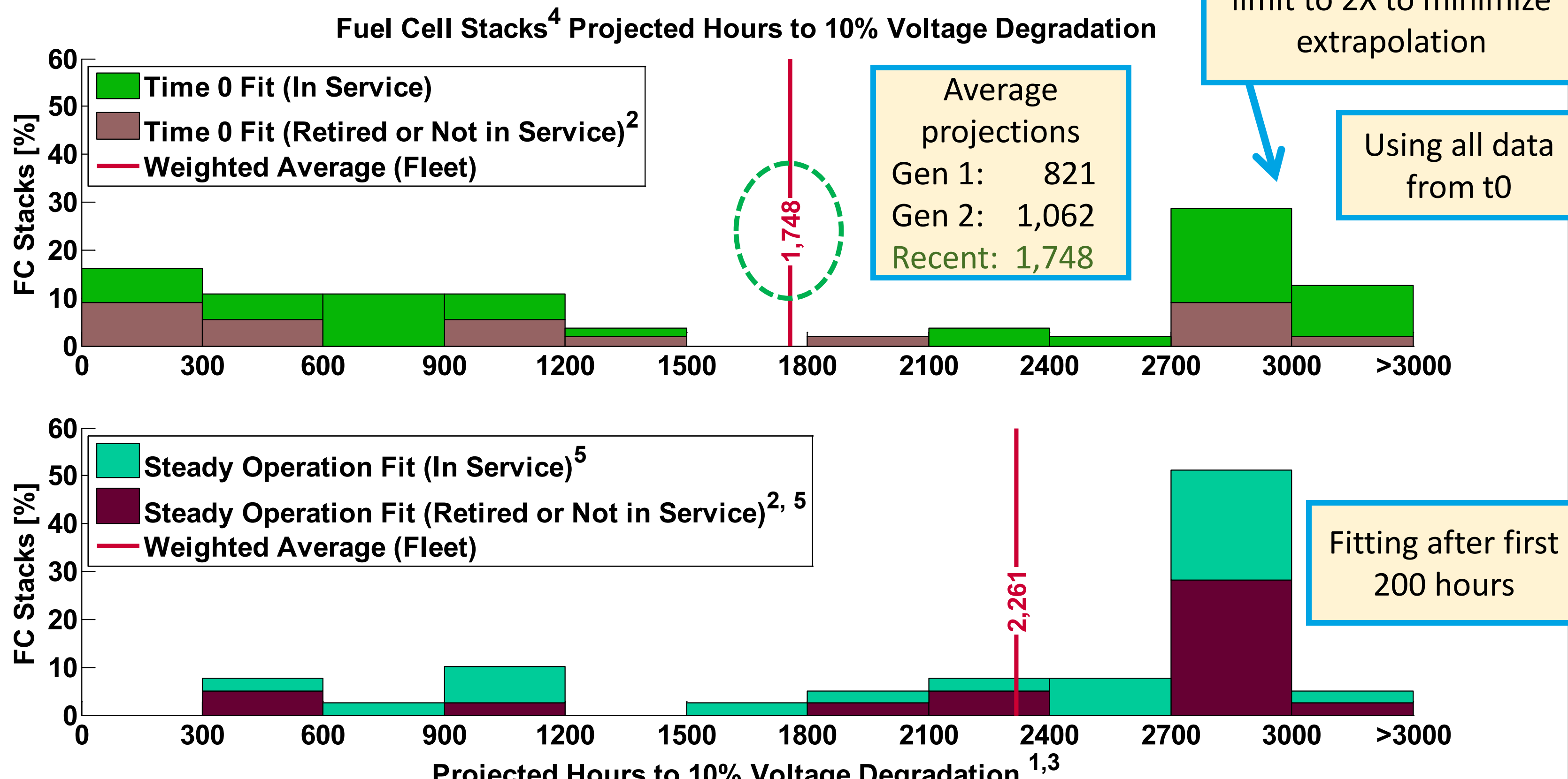


Some stacks operated over 1,400 hours, but half were still below 600 hours

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



Accomplishment: Projected Fuel Stack Durability to 10% Voltage Degradation; Two Fits



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 hou[r is] the period after initial break-in where degradation levels to a more steady rate.

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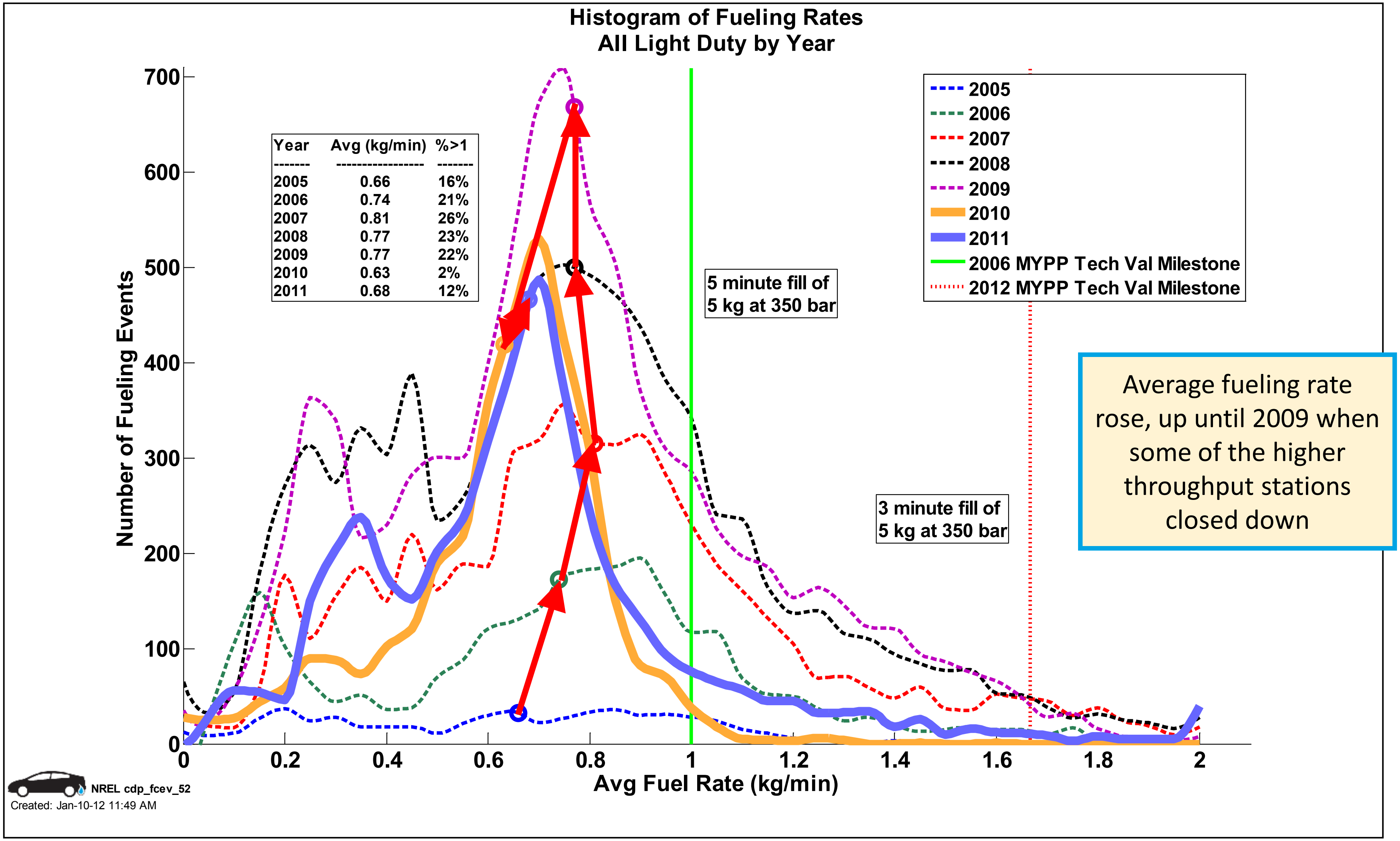
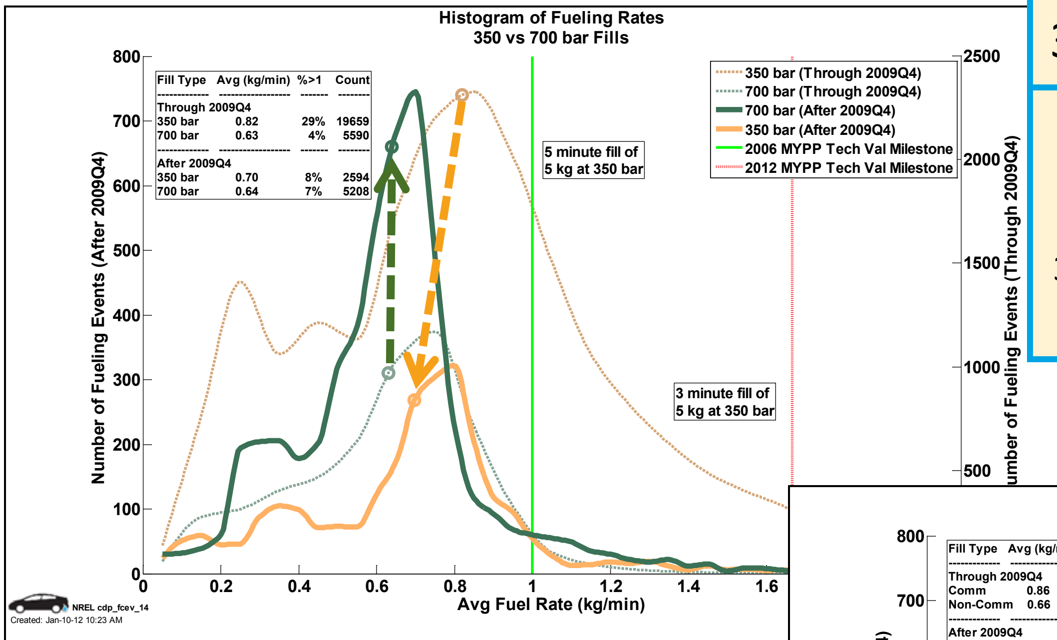
See technical backup for additional details in scatter plot

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



Average fueling rate rose, up until 2009 when some of the higher throughput stations closed down

Accomplishment: Evaluated Fueling Rates by Fill Pressure and Communication vs. Non-Communication – Shifts Observed During Project

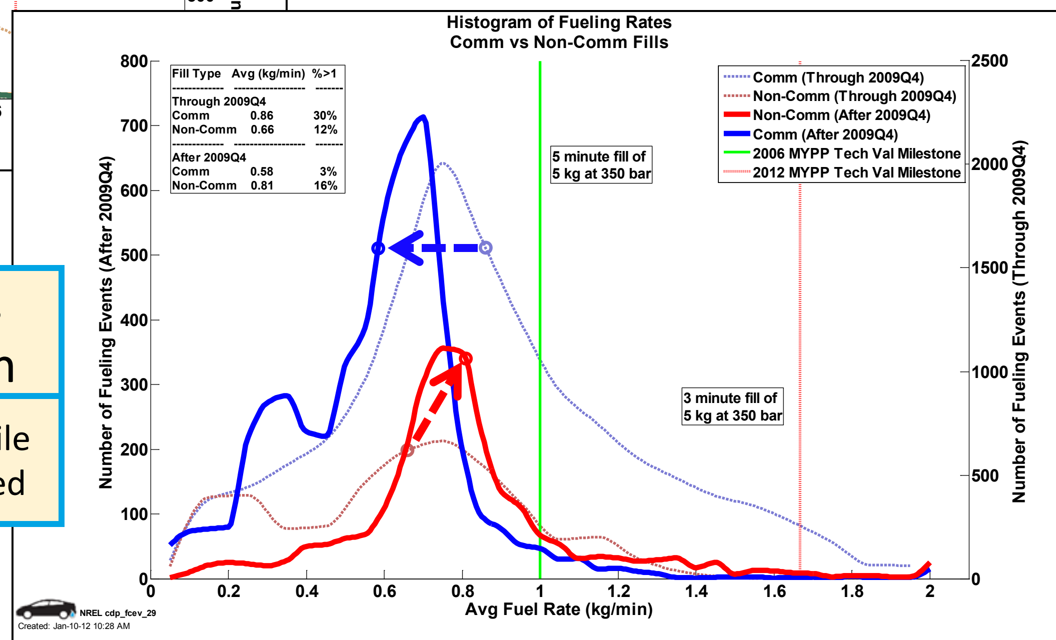


350 vs. 700 bar

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

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

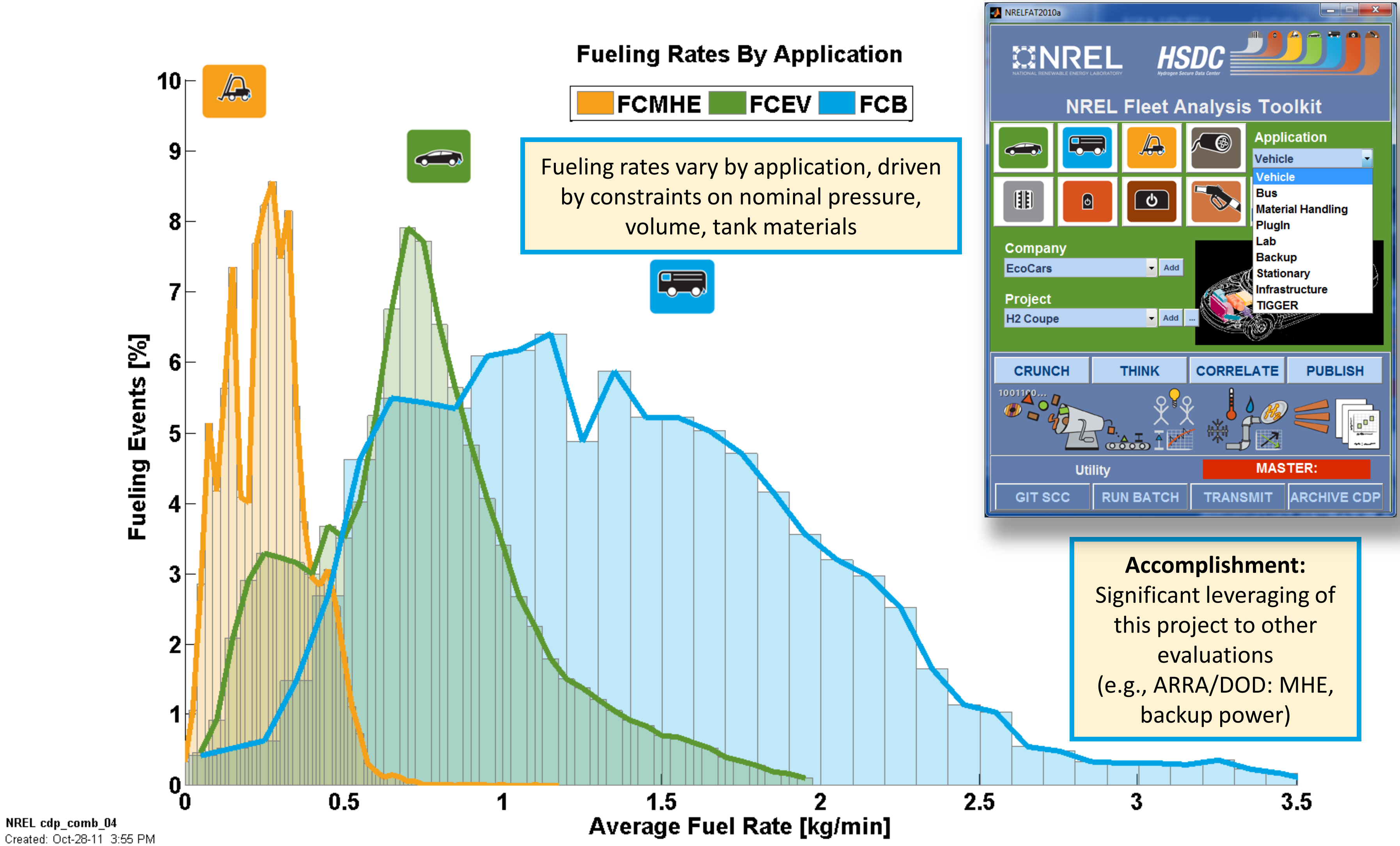
Fueling rates are still evolving due changes in technology and protocols



Communication vs. non-communication

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

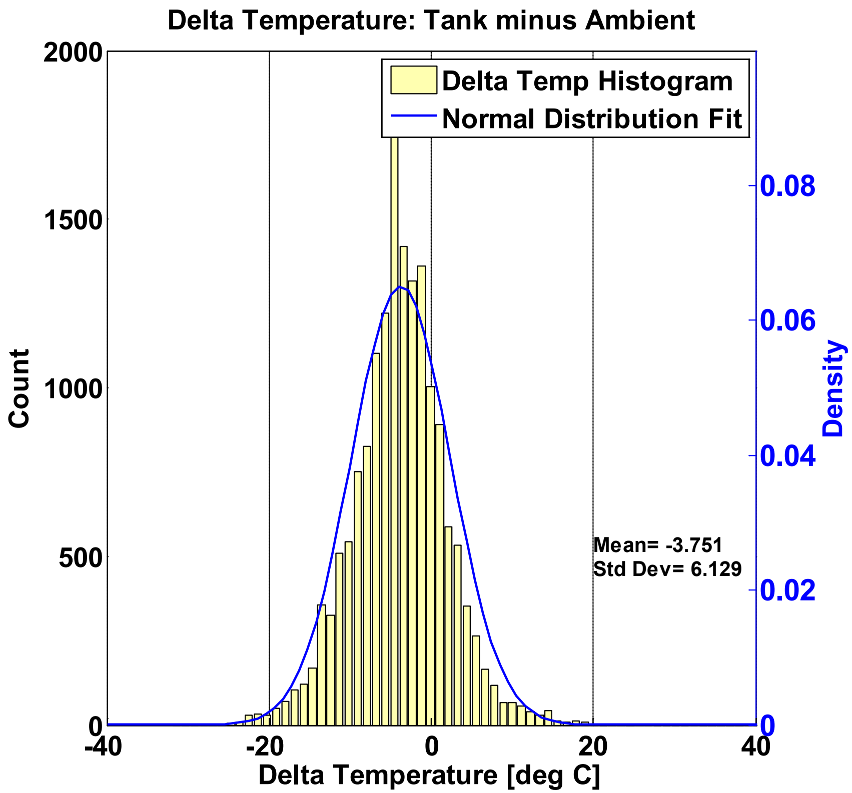
Accomplishment: Leveraged Effort to Other Fuel Cell Applications; Cross-Application CDPs Expanding

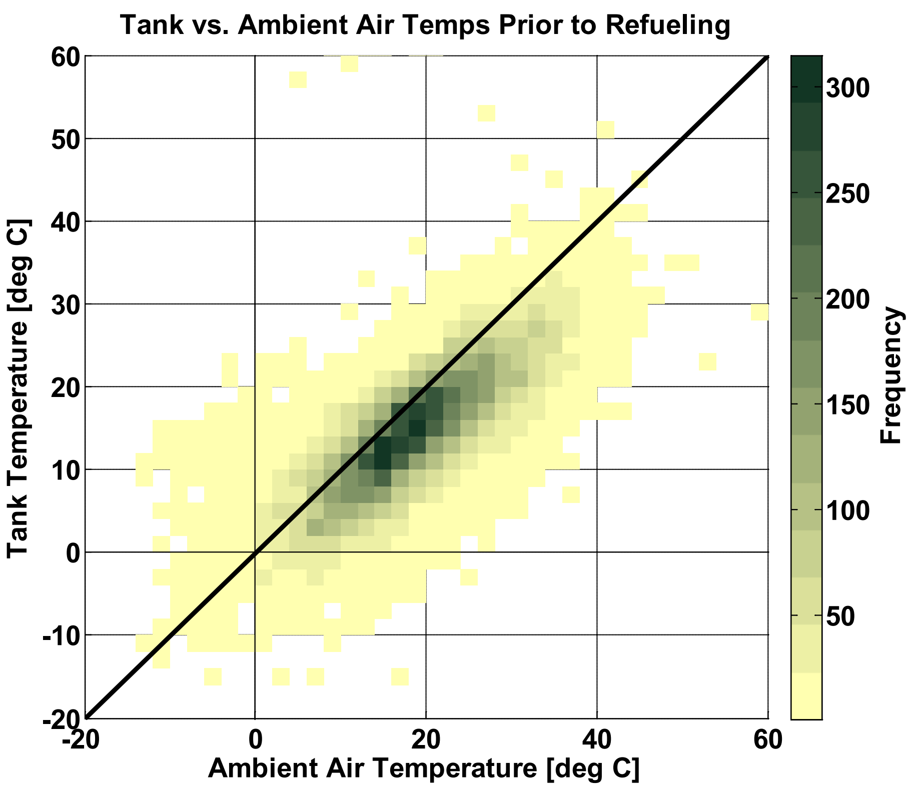


Fueling rates vary by application, driven by constraints on nominal pressure, volume, tank materials

Accomplishment:
Significant leveraging of this project to other evaluations (e.g., ARRA/DOD: MHE, backup power)

Accomplishment: 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

Accomplishment: Communicated Final Project Results to Broad Audience via Multiple Paths

- **Draft final report completed in March**
- **Final report published in April and posted on NREL's web site**
- **Published EVS-26 paper for Los Angeles conference**
- **Held public webinar**
    - 260 participants (400 registered)
    - Active Q&A
- **Created more interactive way to access CDP results from web site**

Highlights of Interactions and Collaborations

- **Auto/Energy Industry Partners**
  - Detailed discussion of NREL results and methodology
  - Discussion of voltage degradation calculations; discussions of how to do new/previous CDPs with fewer teams
  - Review of all results prior to publication
- **U.S. DRIVE Technical Teams**
  - Hydrogen Storage and Fuel Cell Tech Team Briefings Annually
- **FCHEA Technical Working Groups**
  - Transportation Working Group
  - Joint H_2 Quality Task Force
- **California Organizations**
  - CaFCP and CHBC: NREL actively participating as member
  - CARB and CEC: New stations offer potential to provide future data to NREL
- **Early FC Market Evaluations: DOD and ARRA**
  - Leveraged experience to evaluate FC forklifts, backup, and stationary power; begun analyzing PHVs for OEM

Future Work

- **Remainder of FY12:**
  - Support DOE in launching new vehicle evaluation project
    - "Light-Duty Fuel Cell Electric Vehicle Validation Data" (FOA 625)
  - Outside of this project (but related)
    - Transition H_2 station analysis activity to new AOP activity "Next Generation H2 Station Analysis" led by Sam Sprik (see poster TV017 for more info.)
    - Support DOE in launching new infrastructure validation project: "Validation of Hydrogen Refueling Station Performance" (FOA 626, topic 1)
- **FY13:**
  - This project (Learning Demo) will conclude in FY12, so this project will not continue into FY13
  - However, two separate projects on FC vehicles and H2 infrastructure validation will exist in FY13 (referenced above)
  - 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, 3.5M miles, 500K trips
25 Stations: 151,000 kg produced/dispensed, 33K fuelings

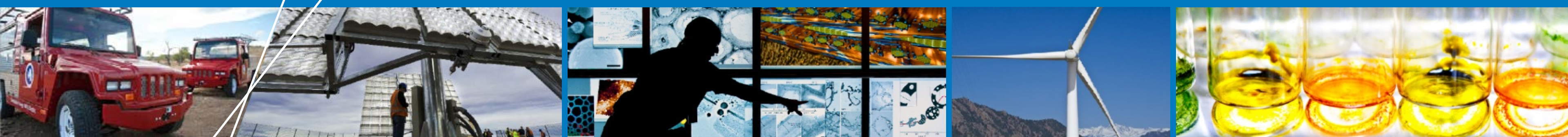
- **Relevance**
  - Provided DOE and taxpayers strong return on investment made in this 7-year project, the largest single FCEV & infrastructure demonstration in the world to date
  - Many system-level DOE program targets validated by this project
- **Approach**
  - Collaborative relationship to analysis 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 (14 more than at last AMR); publication 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]
- **Collaborations**
  - Worked closely with industry partners to validate methodology, and with other key stakeholders to ensure relevance of results
- **Future Work**
  - Support launch of new technology validation projects, including new opportunities to objectively evaluate status of H_2 & FC technology and other vehicle technology
  - HSDC and analysis capability will continue to be used on future projects

Questions and Discussion

Project Contact: Keith Wipke, National Renewable Energy Lab

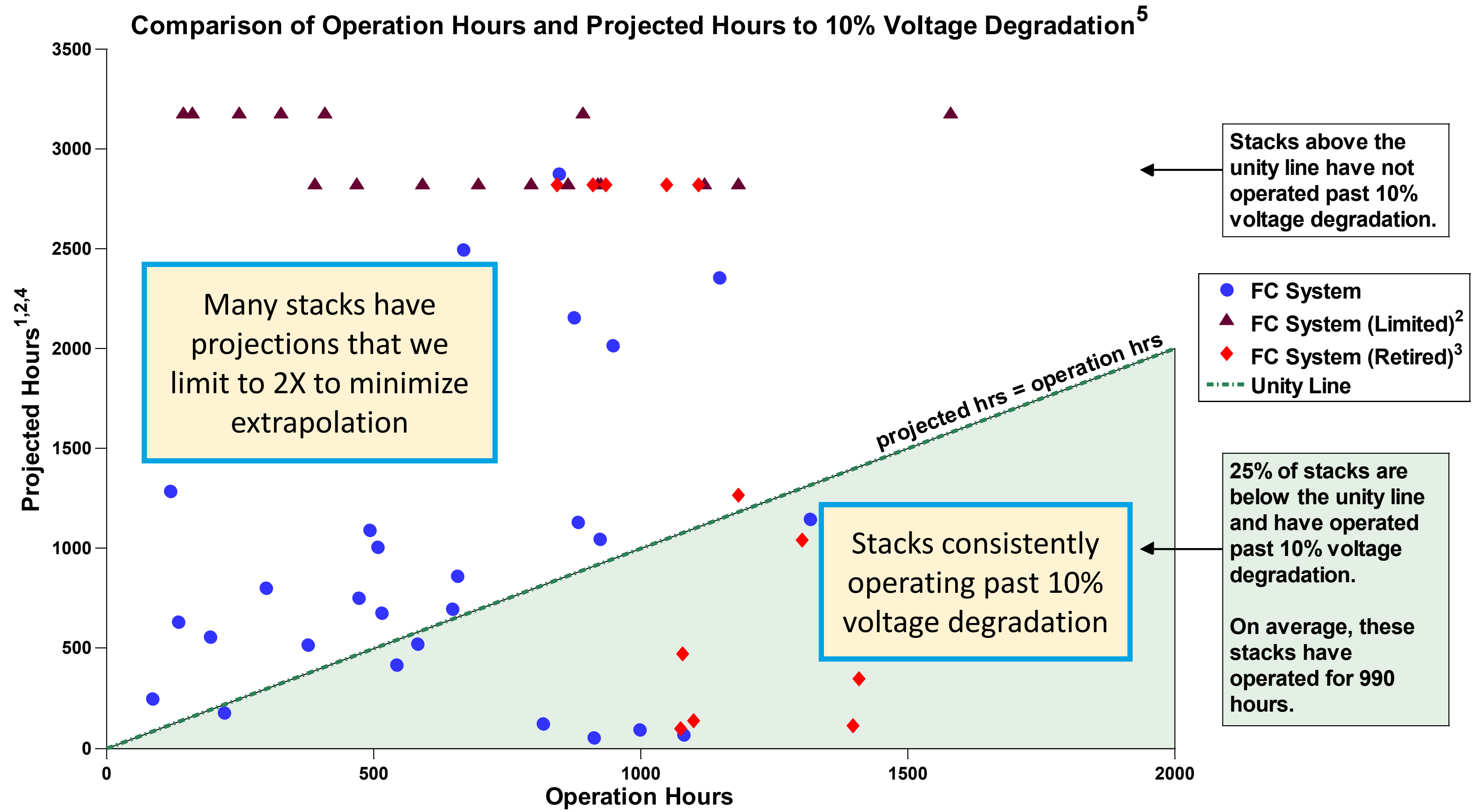
303.275.4451 keith.wipke@nrel.gov

All public Learning Demo papers and presentations are available online at 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) Indicates the projected hours to a 10% voltage degradation based upon curve fitting data from operation hour 0.
2) Projected hours limited based on demonstrated hours.
3) Stacks retired due to low-performance or catastrophic failure.
4) Each projection has uncertainty based on the confidence intervals of the fit.
5) Only includes systems operated after 2009Q4.

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Project Achieved Both Technical Goals; Outside Analysis Used for Cost Evaluation *(updated since 2011 AMR in blue)*

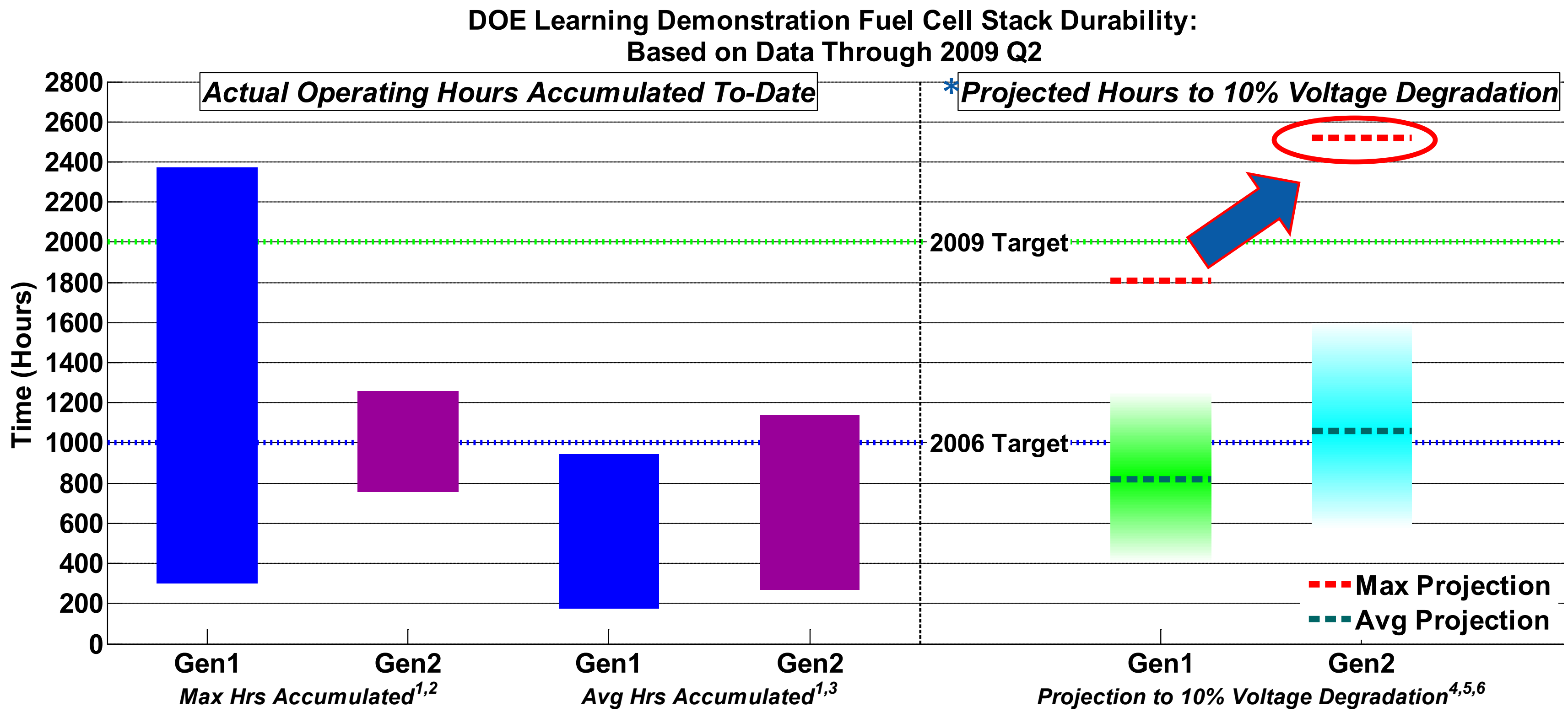
Vehicle Performance Metrics	Gen 1 Vehicle	Gen 2 Vehicle	2009 Target	After 2009Q4
Fuel Cell Stack Durability			**2,000 hours**	
Max Team Projected Hours to 10% Voltage Degradation	**1,807 hours**	**2,521 hours**		--
Average Fuel Cell Durability Projection	821 hours	1,062 hours		1,748 hours
Max Hours of Operation by a Single FC Stack to Date	2,375 hours	1,261 hours		1,582 hours
Driving Range			**250 miles**	
Adjusted Dyno (Window Sticker) Range	**103-190 miles**	**196-254 miles**		--
Median On-Road Distance Between Fuelings	56 miles	81 miles		98 miles
Fuel Economy (Window Sticker)	42 – 57 mi/kg	43 – 58 mi/kg	no target	--
Fuel Cell Efficiency at ¼ Power	51 – 58%	53 – 59%	60%	--
Fuel Cell Efficiency at Full Power	30 – 54%	42 – 53%	50%	--

Infrastructure Performance Metrics			2009 Target	After 2009Q4
H_2 Cost at Station (early market)	On-site natural gas reformation **\$7.70 – \$10.30/kg**	On-site Electrolysis **\$10.00 – \$12.90/kg**	**\$3/gge**	--
Average H_2 Fueling Rate	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

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



(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.

NREL CDP01
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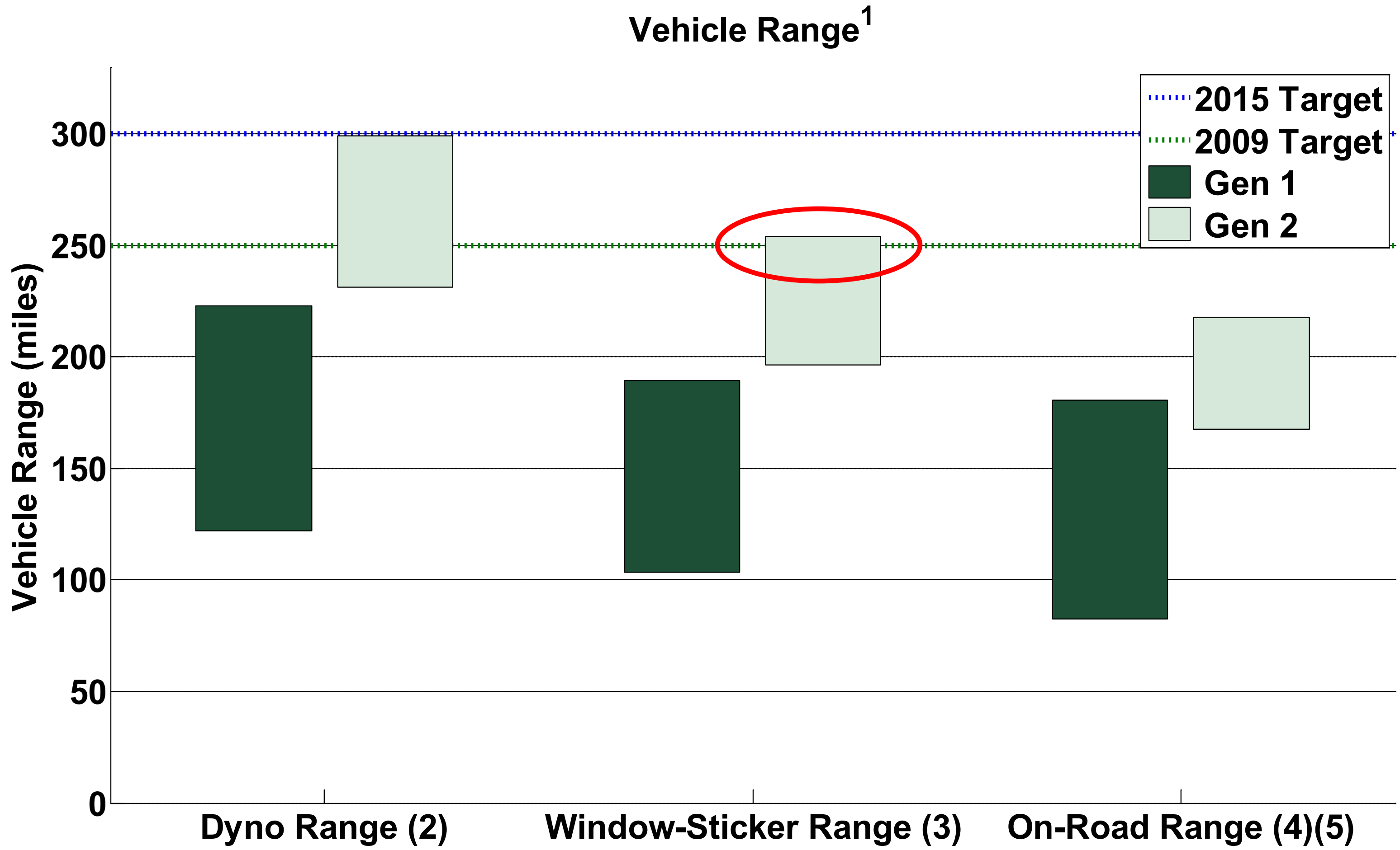
* Durability is defined by DOE as projected hours to 10% voltage degradation

Spring 2010

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



(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 x Hwy, 0.9 x 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.

NREL CDP02
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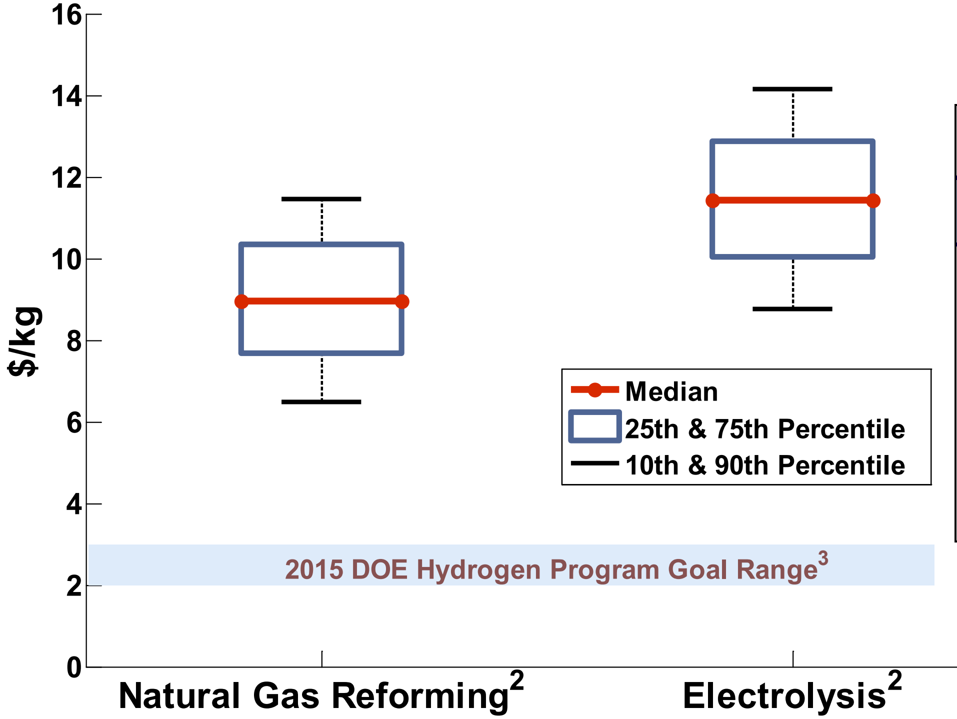
Spring 2010

3) Projected Early Market H_2 Production Cost from Learning Demo Energy Partners' Inputs (2010 AMR)

Projected Early Market 1500 kg/day Hydrogen Cost[1] *



Key H2 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 H2A 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 H2A Production model inputs supplemented with feedback from Learning Demonstration energy company partners, based on their experience operating on-site hydrogen production stations. H2A-based Monte Carlo simulations (2,000 trials) were completed for both natural gas reforming and electrolysis stations using default H2A 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.

NREL CDP15
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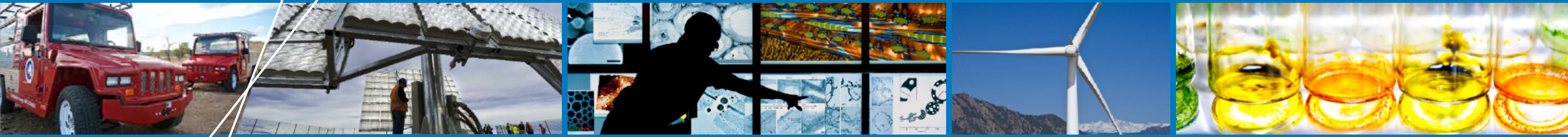
Outside of this project, DOE independent panels concluded at 500 replicate stations/year:
Distributed natural gas reformation at 1500 kg/day: **$2.75-$3.50/kg** (2006)
Distributed electrolysis at 1500kg/day: **$4.90-$5.70** (2009)

Spring 2010



Reviewer-Only Slides

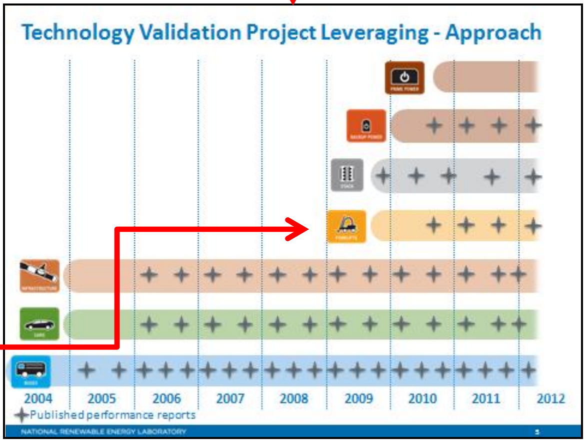
Responses to Previous Year (FY11) Reviewers' Comments

- Q: "The project is nearly finished, and future work should focus on effectively disseminating information to key automotive decision makers"
- A: We have communicated results very broadly this year, as discussed in this presentation, including the webinar, EVS-26 paper, final report, and website.

- Q: "It is hoped that DOE will be able to continue funding technology validation projects at NREL" and "The project should continue in some form. Future years will be critically important as FCVs approach commercialization. Reliable and accurate data will be required for continued technology development."
- A: DOE continues to support technology validation projects at NREL beyond this Learning Demonstration project conclusion. DOE has recently announced two FOAs (625 and 626) that will provide data to NREL on FCEVs and H2 stations for analysis. NREL will also continue validation of FC buses, FC MHE, FC backup power, FC stationary power, and Wind2H_2.

- Q: "More information on the reasons vehicles are retired from the database would be helpful. Also, more information on the power drop off at 350 bar would be appreciated."
- A: Vehicles are retired from the database for many reasons, including: contracts ending, vehicles being redeployed outside of the DOE project, traffic accidents, degradation or failure on both FC and non FC systems (e.g. batteries). The 2nd question is not clear what is being asked: FC power is not a function of tank pressure.

- Q: "Researchers should add analysis of material handling equipment to the NREL portfolio"
- A: FC MHE analysis was added to NREL's portfolio in late 2009. See Jen Kurtz' (ARRA) and Todd Ramsden's (Oorja) AMR presentations in 2011 and 2012.



Publications and Presentations

(Since FY11 AMR, newest to oldest, key text in bold)

1. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., Saur, G., "Final Results from U.S. FCEV Learning Demonstration," **26th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium (EVS-26)**, Los Angeles, CA, May 2012. (paper and presentation)
2. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., Saur, G., "**National Fuel Cell Electric Vehicle Learning Demonstration Final Report**," NREL Technical Publication, Golden, CO, April 2012. (paper)
3. Kurtz, J., Wipke, K., Eudy, L., Sprik, S., Ramsden, T., "Fuel Cell Technology Demonstrations and Data Analysis," **Chapter in *Hydrogen Energy and Vehicle Systems*,** Green Chemistry and Chemical Engineering, CRC Press, April 2012. (book chapter)
4. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., Saur, G., "National Hydrogen Learning Demonstration Status," **DOE's Informational Webinar Series**, February 2012. (presentation and webinar recording)
5. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., Saur, G., "**Winter 2011 – All Composite Data Products**: National FCEV Learning Demonstration, with Updates through January 18, 2012," Golden, CO: National Renewable Energy Laboratory, published January 2012. (presentation)
6. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., Saur, G., **2011 Annual Progress Report** for NREL's "Controlled Hydrogen Fleet and Infrastructure Analysis Project," November 2011). (paper)
7. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., Saur, G., "Conclusion of the National FCEV Learning Demonstration Project," presented at the **Fuel Cell Seminar**, Orlando, Florida in November 2011. (presentation)
8. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., Saur, G., "**Fall 2011 – All Composite Data Products** with Updates through October 5, 2011: National FCEV Learning Demonstration," Golden, CO: National Renewable Energy Laboratory, published October 2011. (presentation)
9. Sprik, S., Kurtz, J., Wipke, K., Ramsden, T., Ainscough, C., Eudy, L., and Saur, G., "Real-World Hydrogen Technology Validation", **International Conference on Hydrogen Safety (ICHS 2011)**, September 2011. (presentation and paper)