NREL
NATIONAL RENEWABLE ENERGY LABORATORY





Fuel Cell Technology Status: Degradation

Jennifer Kurtz (PI), Huyen Dinh, Genevieve Saur, Chris Ainscough

June 8, 2017

DOE 2017 Annual Merit Review

Washington, DC

Project ID FC081

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

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Overview

Timeline and Budget

- Project start date: 7/2009[1]
- FY16 DOE funding: $100k
- FY17 DOE funding: $100k
- Total DOE funds received to date: $835k

Partners

- U.S. and international fuel cell and electrolyzer developers supply data voluntarily and review published results

Barriers

- Lack of data for current fuel cell stack voltage durability

Application	2020 Durability Target[2]
Light Duty Automotive	5,000 Hours
Public Transit	25,000 Hours
Stationary 1-10kW	0.3%/1,000 Hours (10% - 33,000 Hours)
Stationary 100 kW – 3 MW	80,000 Hours
Electrolysis	TBD

[1]Project continuation determined annually by DOE

[2]Fuel Cell Technology Office Multi-Year RD&D Plan – Section 3.4

FC Tech Status Objectives and Relevance

- Question – What is the current status and progress of fuel cell and electrolyzer durability and cost improvements across multiple developers?
- Analysis Method – Independent analysis of voluntarily supplied fuel cell and electrolyzer operation data
  - Aggregated to protect proprietary data
  - Uniformly apply analysis method to developers' voluntarily supplied data from lab testing (technology readiness level ~ 3 – 5)
- Disseminating Results – Publish aggregated analysis results from multiple developers on durability and cost
  - Reviewed by data suppliers
  - Presented against DOE targets

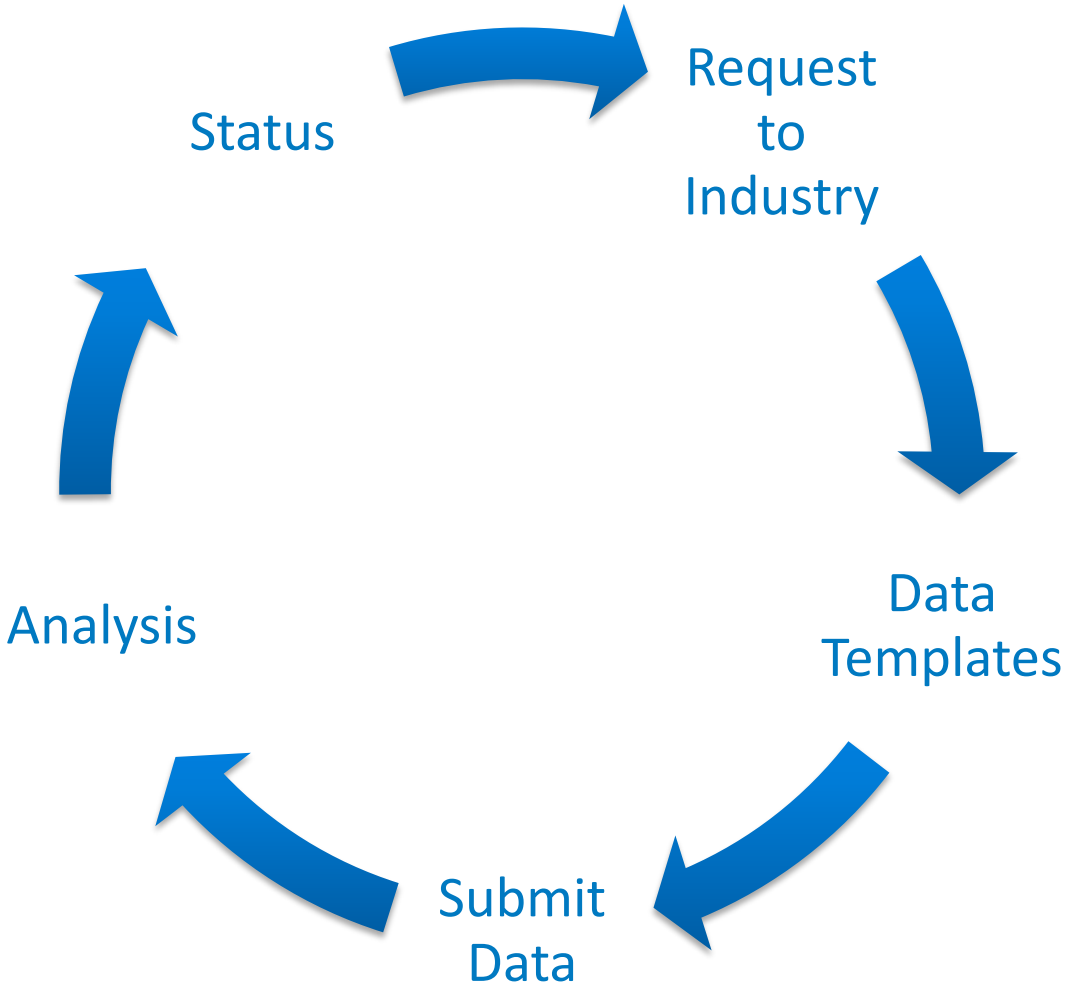
FY17 Objectives

- Receive and analyze new lab durability data
- Update and publish the durability results
- Include electrolysis data & update price data

Barrier/Impact

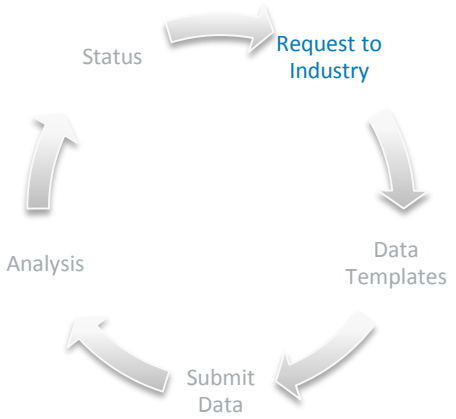
- Data on fuel cell stack voltage durability is received at the National Fuel Cell Technology Evaluation Center (NFCTEC)
- Consistent and independent source for current and legacy voltage durability
- Status used for DOE records (e.g. https://www.hydrogen.energy.gov/pdfs/11003_fuel_cell_stack_durability.pdf)

State-of-the-art Lab FC & Electrolysis Degradation Annual Benchmarking



Data collection, analysis, aggregation, and reporting consistent with FY16 approach

Approach – Data Request



Request to Industry

- Contacted via Email, Call, or Industry Gatherings
- Reach out to all leading developers

Sample Email Request

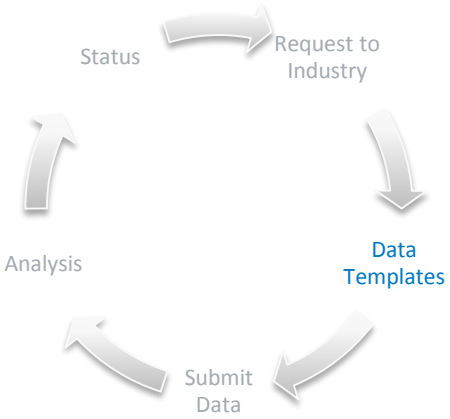
You are receiving this email because you have been identified as a leading fuel cell developer and a key participant for a fuel cell technology status benchmarking project by the National Renewable Energy Laboratory (NREL). This is one of NREL's technology validation projects where the results are referenced and used regularly by the Department of Energy (DOE).

*We are requesting your participation in this analysis activity by providing data from **lab testing of fuel cell stacks** to benchmark the state-of-the-art fuel cell stack durability.* To help make the process easier & quicker for you, attached is an excel spreadsheet outlining the metadata for the durability data we would like to collect. The attached information pamphlet summarizes the features and benefits to you for participating in this project and the minimum type of durability data we'd like from you. These can be systems, full stacks, short stacks or single cell lab data with significant operation hours. If you choose to share data, the data is not restricted to DOE funded projects and is completely voluntary.

We understand that durability is sensitive information. The attached information pamphlet summarizes our process for protection of proprietary data. Our process includes aggregation of data analysis results that do not identify individual participants and a two stage review and approval period prior to publication. If you do not approve it or if we do not have enough participants in a particular analyses to protect the data, then we will not publish it. NREL Technology Validation team is a trusted, neutral third party that US. DOE and others rely on to get updated progress on fuel cell technology. All data is in the National Fuel Cell Technology Evaluation Center (NFCTEC) that is off-the network, has limited access (8 people on the Technology Validation team can access this center) and houses the data and where analyses are done. We do this to protect our partners' proprietary information.

Rest assured that we know how to protect your data and many companies participate in this project. NREL's technology validation team has been doing this since 2004. All presentations, published CDPs, and project information can be found at http://www.nrel.gov/hydrogen/proj_fc_analysis.html

Approach – Data Gathering



What Data

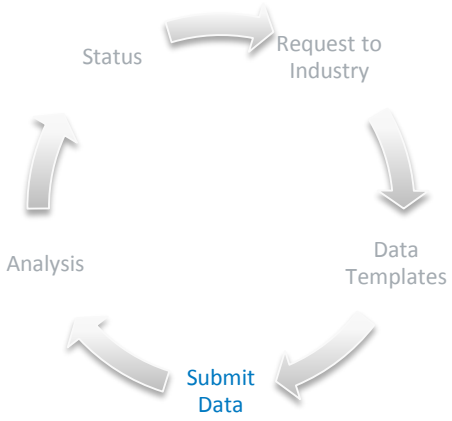
- Existing data from industry
- Voluntarily supplied
- Technology Readiness Level ~ 3 – 5
- Voltage, current, hours, metadata, market

Example metadata template

MetaData	Input	Notes
Data Set ID		
Expected application		
Fuel cell type		
Fuel		
Description		
Configuration		
Test condition		
Describe accelerated testing (if applicable)		(e.g. extreme temperature, cycles, relative humidity, pressure, fuel and oxidant flow, standard AST, or a combination)
Describe standard ASTs used (if applicable)		(e.g. DOE ASTs)
Lab ambient conditions		
Operation status		
Reason not in operation (if applicable)		
Reason for failure (if applicable)		
Power range (kW)		
Current (or current density) points for studying degradation		Minimum is one high operation current point
Cell Count		
Active Area (cm2)		

Optional Asks
Membrane type
Membrane thickness (micron)
Anode catalyst loading (mg/cm2)
Cathode catalyst loading (mg/cm2)
Catalyst material
GDL material
Current collector material
Flow field type
Flow rate (anode and cathode)
Cell temperature (°C)
Back pressure (kPa)
Relative humidity (%)

Approach – Data Gathering



Submit Data

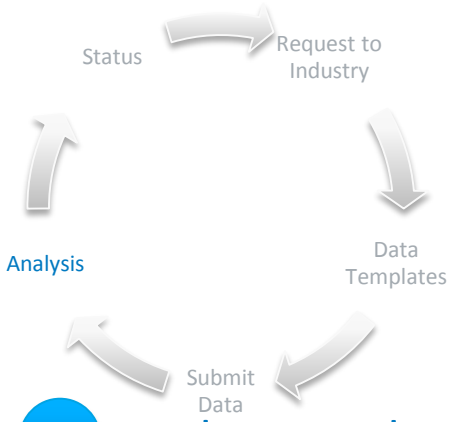
- Industry selected data sent to NFCTEC
- Data from variety of configurations and test protocols
- No specific test requirements, other than a high number of hours (e.g. > 1,000 hours)
- Fuel cell technologies include Polymer Electrolyte Membrane (PEM), Solid Oxide (SO), and Direct Methanol (DM), Electrolysis

Fuel Cell/Electrolyzer Technology Status Data Supply

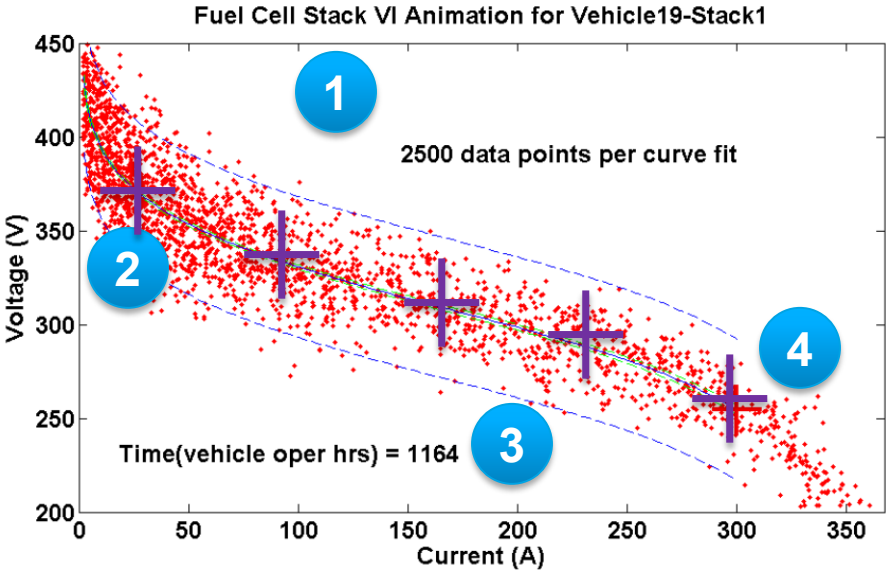
Voluntarily supplied from fuel cell developers
Durability – voltage, current, and hours minimum data needed
Test – time frame, objective, protocol, application, and type
Market – system price, availability, and application

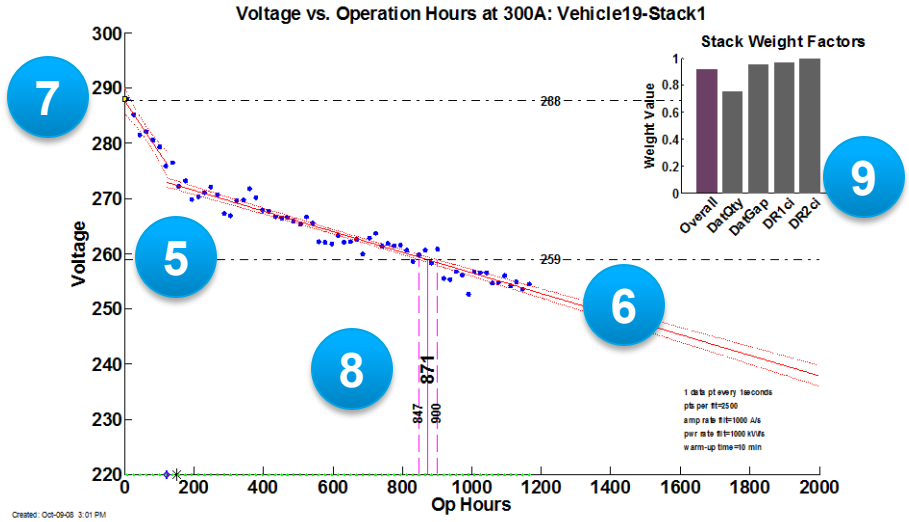
National Fuel Cell Technology Evaluation Center

Approach – Data Analysis



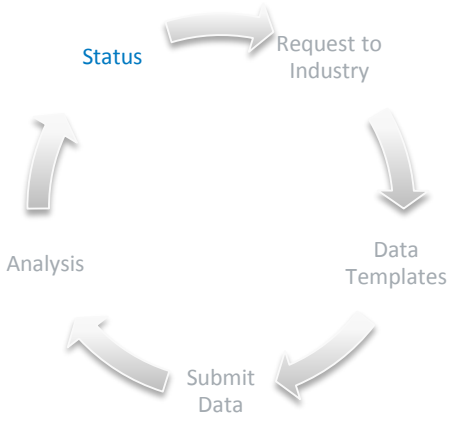
Analysis – EXAMPLE DATA





1. Voltage and current data
2. Apply polarization fit
3. Corresponding operation hour
4. Voltages from polarization fit at set currents
5. Fit voltage and operation data
6. Degradation linear fit
7. Y-intercept beginning of life voltage
8. Record operation hour when fit crosses 10% nominal voltage drop
9. Investigate fit quality

Approach – Status



Status
- Detailed Data Products (DDPs)
  - Individual results provided to data provider
  - Benchmark individual status
  - Data provider review and concurrence prior to publication
- Composite Data Products (CDPs)
  - Published aggregated results across multiple systems and teams without revealing proprietary data
  - Annual update*

Fuel Cell/Electrolyzer Technology Data Provider

National Fuel Cell Technology Evaluation Center

Results

Confidential

DDPs

Public

CDPs

*www.nrel.gov/hydrogen/proj_tech_validation.html

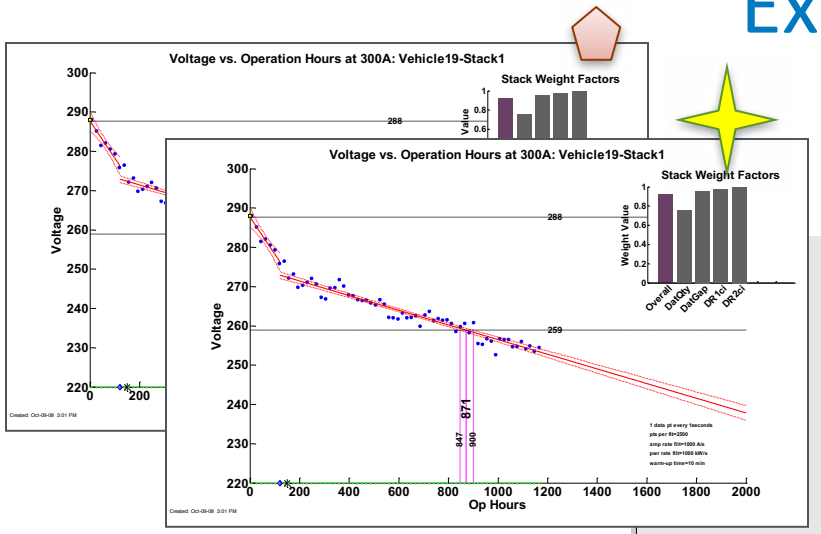
Approach: CDP and DDP Review

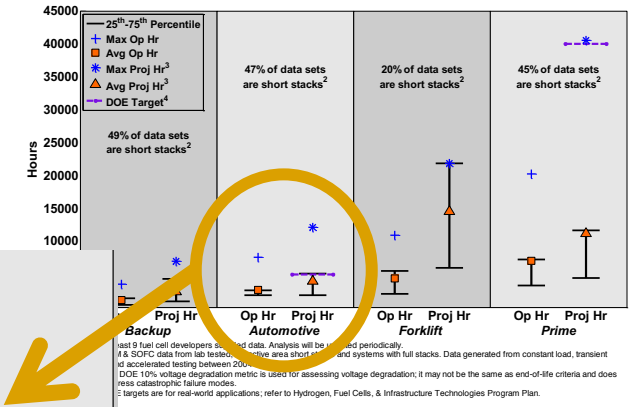
Data Process and Analysis

Example Data Results (if needed) → Draft CDPs → Initial Review (~1 week) → Final Draft CDPs (<1 week) → Final Review (<1 week) → Finalized CDPs (<1 week)

(~4 weeks excluding data processing and analysis)

Example DDPs





Sample Data Set 1

Sample Data Set 2

Op Hr **Proj Hr**

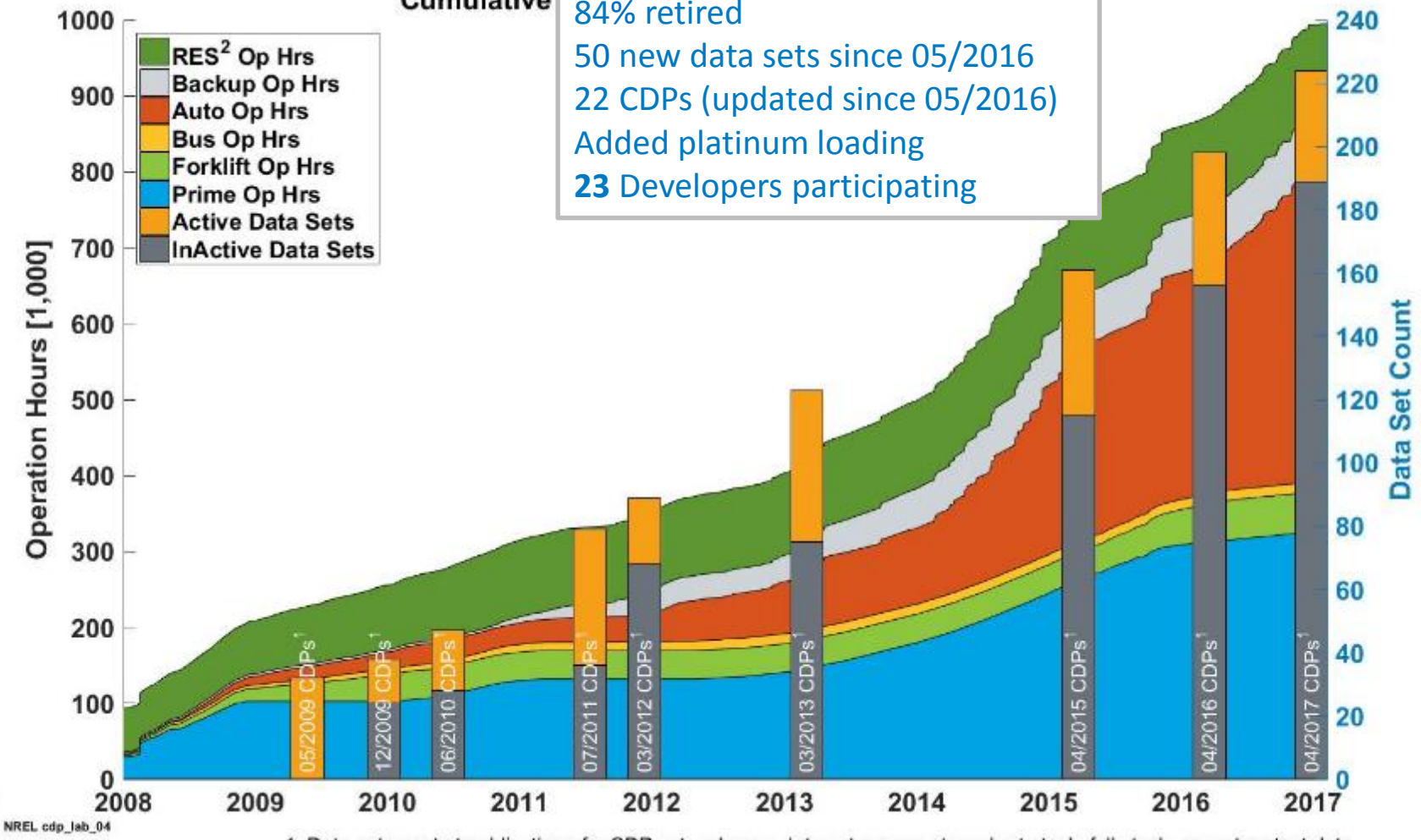
Automotive

✓ **FY17 Milestone**

Analysis complete and updated results published by 05/2017

Accomplishment: Data Set Count and Operation Hours

05/2017 CDPs include
224 data sets analyzed
84% retired
50 new data sets since 05/2016
22 CDPs (updated since 05/2016)
Added platinum loading
23 Developers participating



NREL cdp_lab_04
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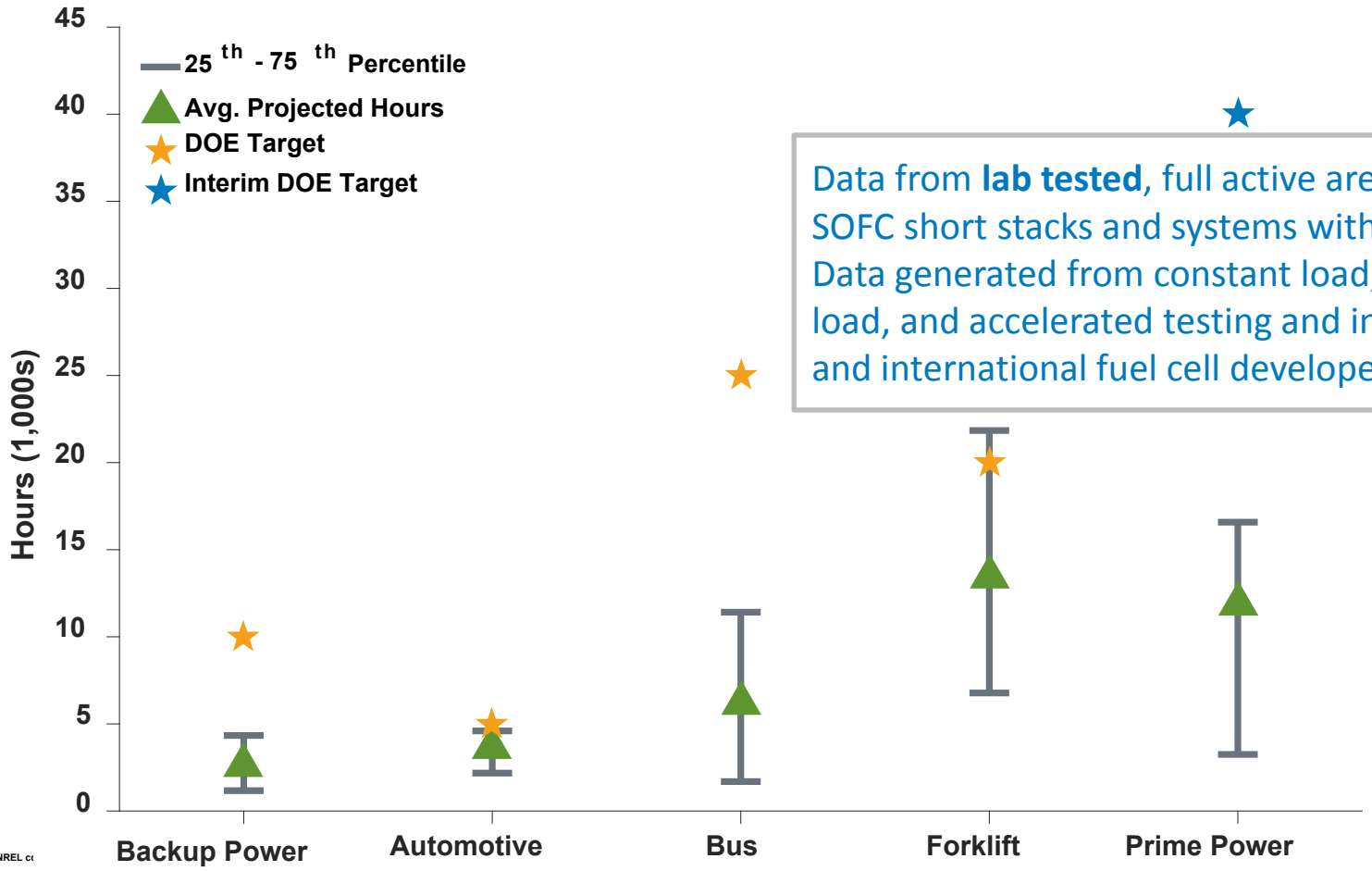
1. Data set count at publication of a CDP set - where a data set represents a short stack, full stack, or system test data.
2. Renewable Energy Storage via Electrolysis

Updated

Accomplishment: Voltage Degradation Results by Application

The average projected times (hrs) to 10% voltage drop are **2,600**, **3,700**, **6,200**, **13,500**, and **11,900** for **backup power**, **automotive**, **bus**, **forklift**, and **stationary** applications, respectively.

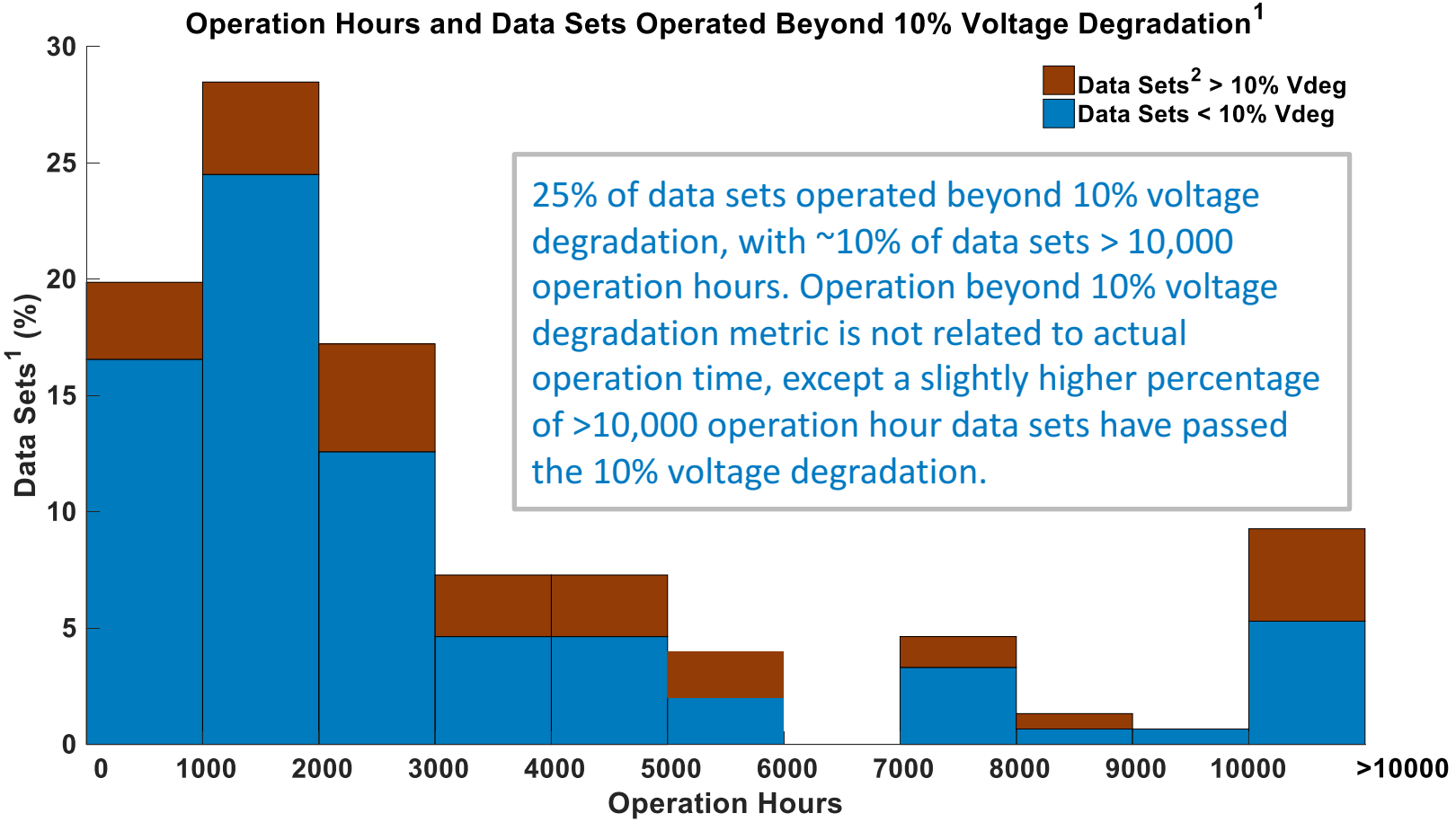


Data from **lab tested**, full active area PEMFC and SOFC short stacks and systems with full stacks. Data generated from constant load, transient load, and accelerated testing and include 23 U.S. and international fuel cell developers.

Updated

10% voltage degradation metric is used for assessing voltage degradation; it may not be the same as end-of-life criteria and does not address catastrophic failure modes. DMFC included but not enough data was available for publication. DOE targets are for real-world applications; refer to Fuel Cell Technologies Office Multi-Year RD&D Plan.

Accomplishment: Study of data sets that have operated beyond 10% voltage degradation



25% of data sets operated beyond 10% voltage degradation, with ~10% of data sets > 10,000 operation hours. Operation beyond 10% voltage degradation metric is not related to actual operation time, except a slightly higher percentage of >10,000 operation hour data sets have passed the 10% voltage degradation.

1. A data set represents a short stack, full stack, or system test data.
2. The DOE 10% voltage degradation metric is used for assessing voltage degradation; it may not be the same as end-of-life criteria and does not address catastrophic failure modes. Some data sets have operated beyond 10% voltage degradation because they are able to satisfy the operating requirements at a higher percentage of voltage degradation or the test is designed to operate until a failure.

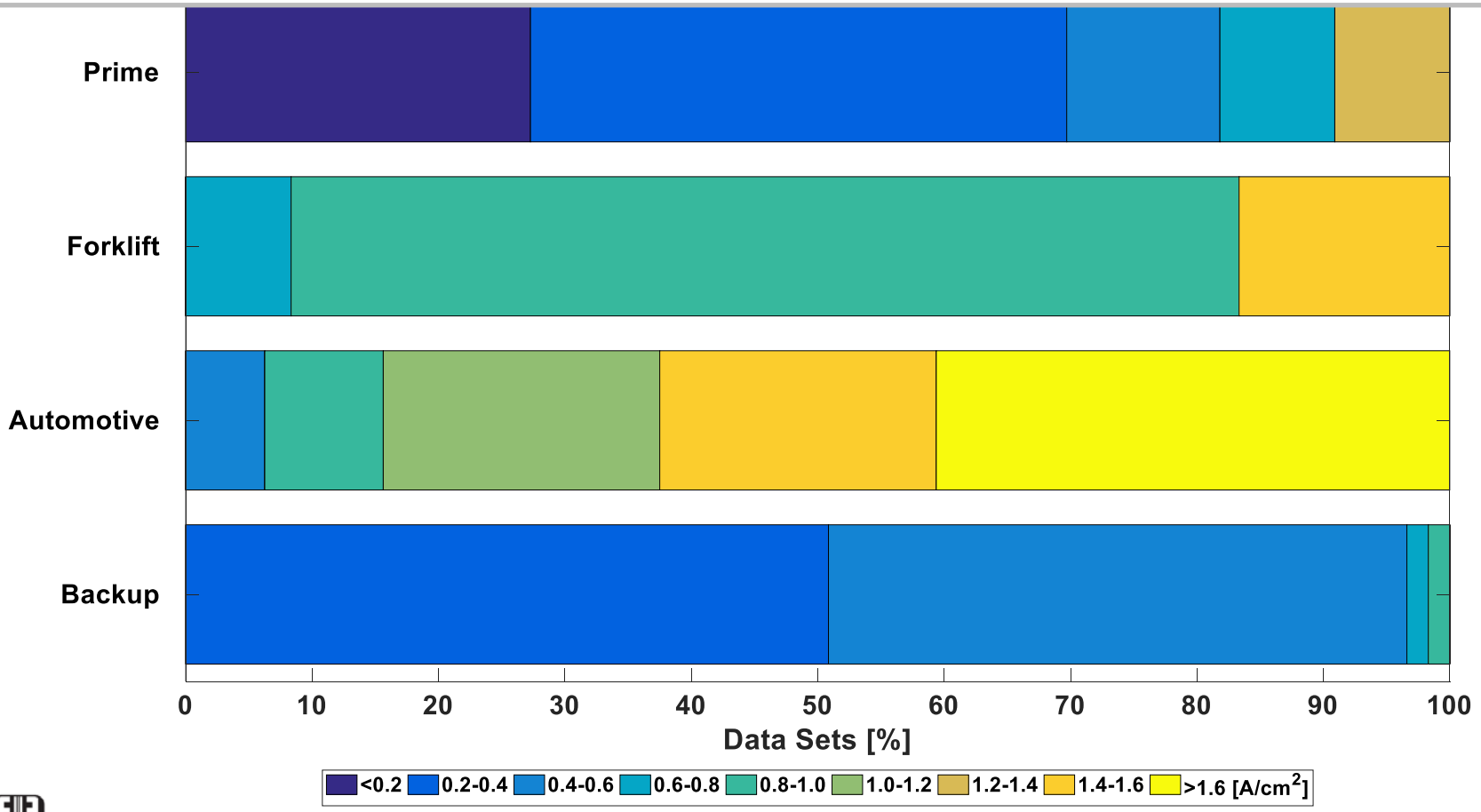
NREL cdp_lab_07

Created: May-05-17 4:00 PM | Data Range: 2004Q1-2016Q4

Updated

Accomplishment – Current Density Variation between Data

The current density variation of data sets is primarily due to the configuration, testing protocols, and application. The automotive data sets are primarily in the higher current density bins because of vehicle packaging constraints for power density. Over 60% of automotive data sets were studied at >=1.2 A/cm^2 in 2017 result (<50% in 2016 analysis result).



NREL cdp_lab_14

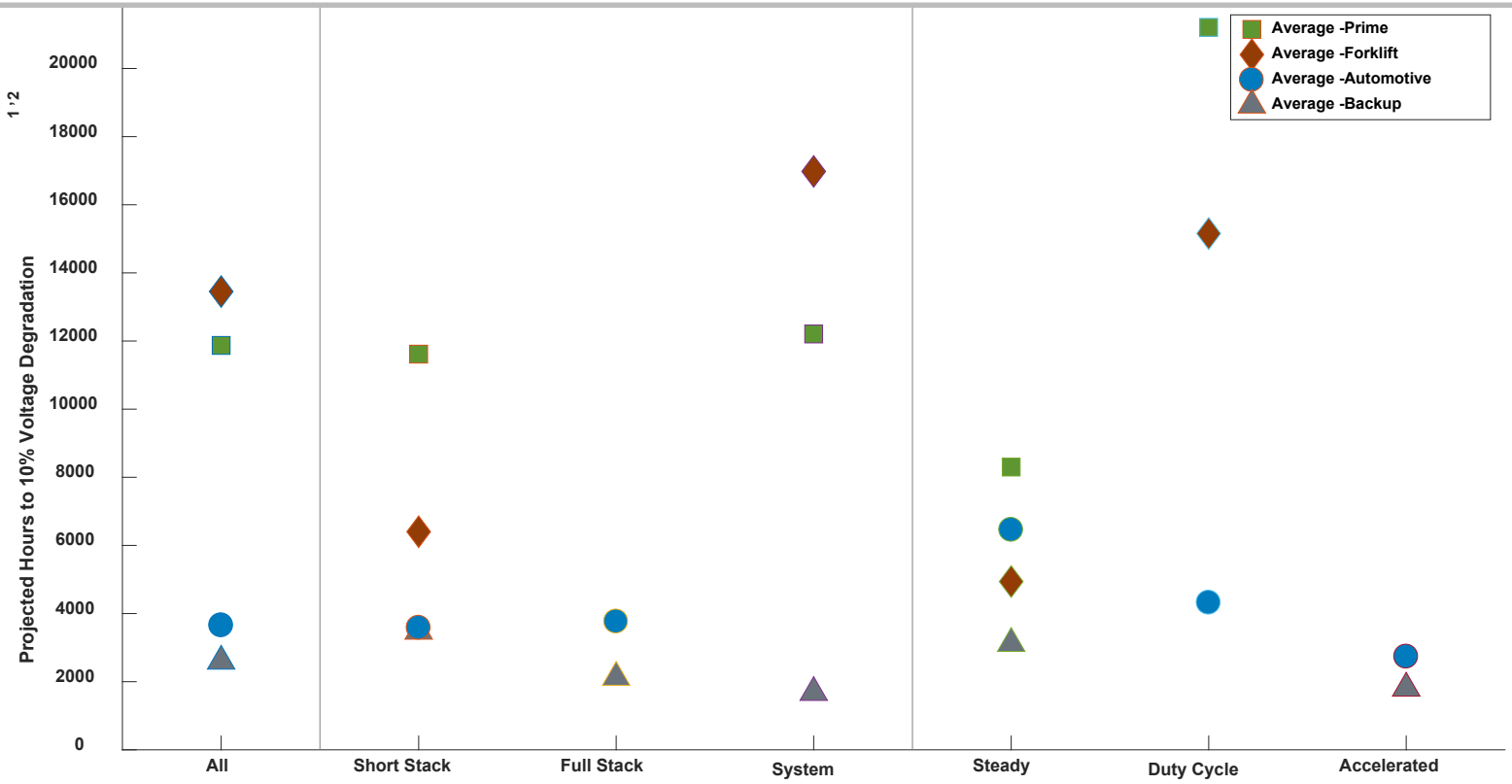
Created: May-05-17 4:08 PM | Data Range: 2004Q1-2016Q4

1) Current density referenced are the points at which the voltage degradation is analyzed in CDP Lab 01

Update

Accomplishment: Voltage Degradation by Configuration and Test Condition

Automotive category: Short stack and full stack don't vary much but there is a significant variation in projected hours to 10% voltage degradation between the different test conditions.

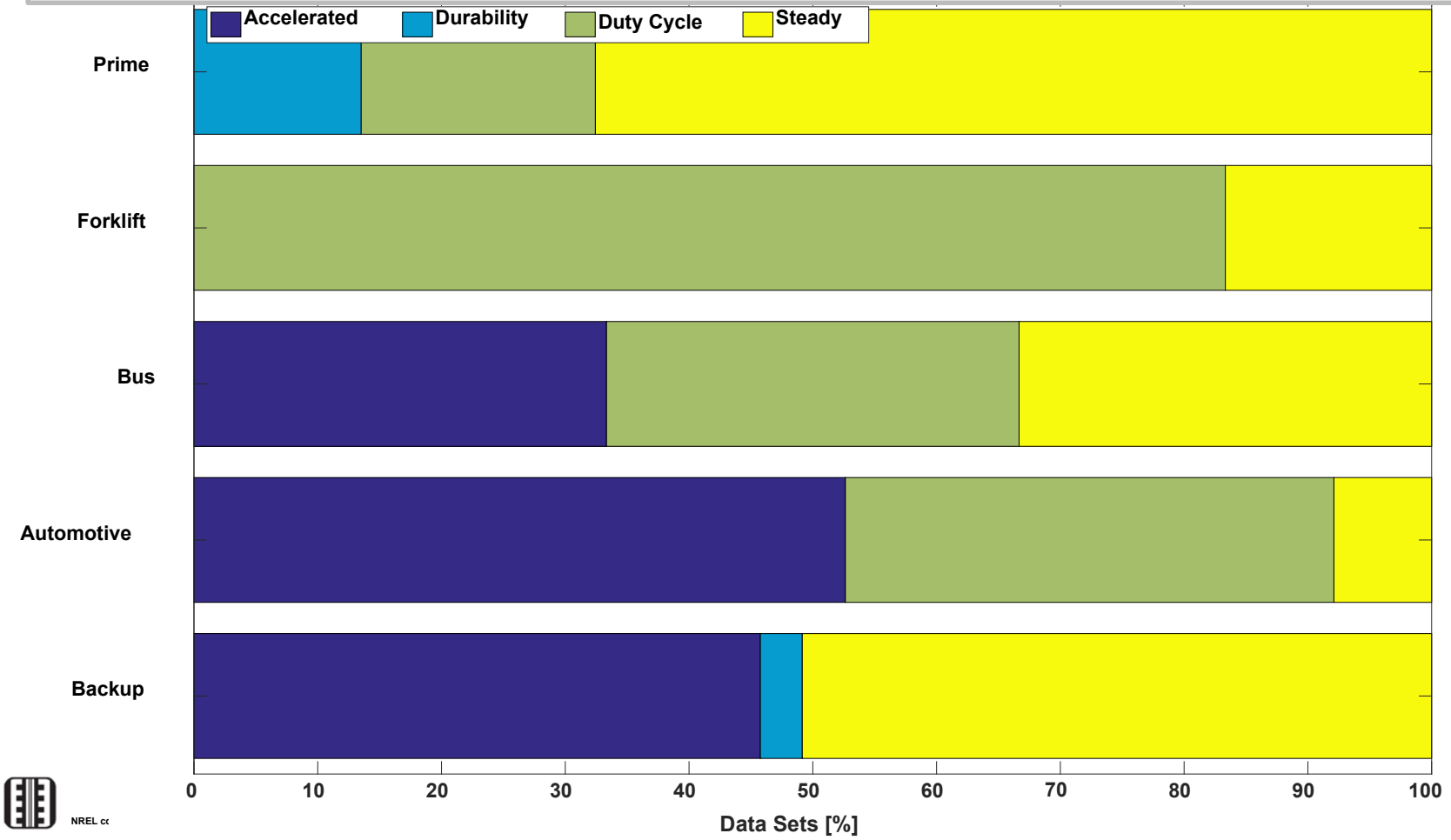


Not all applications have data sets in each configuration or test condition group.
Steady – little or no change to load profile
Duty Cycle – load profile mimics real-world operating conditions
Accelerated – test profile is more aggressive than real-world operating conditions and data not corrected for accelerated conditions

Updated

Accomplishment: Test Conditions by Data Set

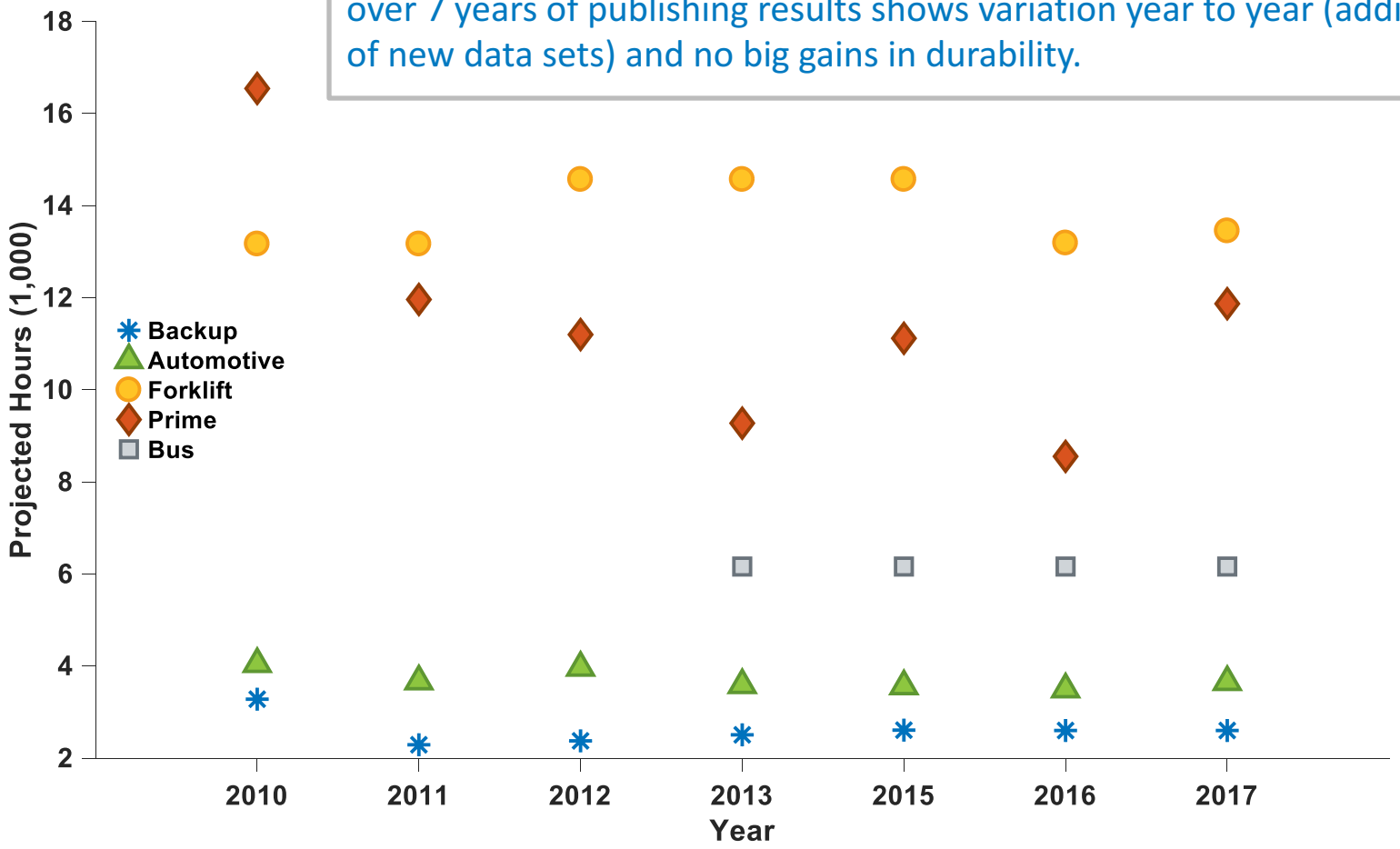
Automotive category: Accelerated test conditions is just over 50% of the automotive data sets analyzed, which is the highest of the application categories studied.



Updated

Accomplishment – Voltage degradation trend over time

A comparison of average time to 10% voltage degradation by application over 7 years of publishing results shows variation year to year (addition of new data sets) and no big gains in durability.



NREL cdp_lab_16

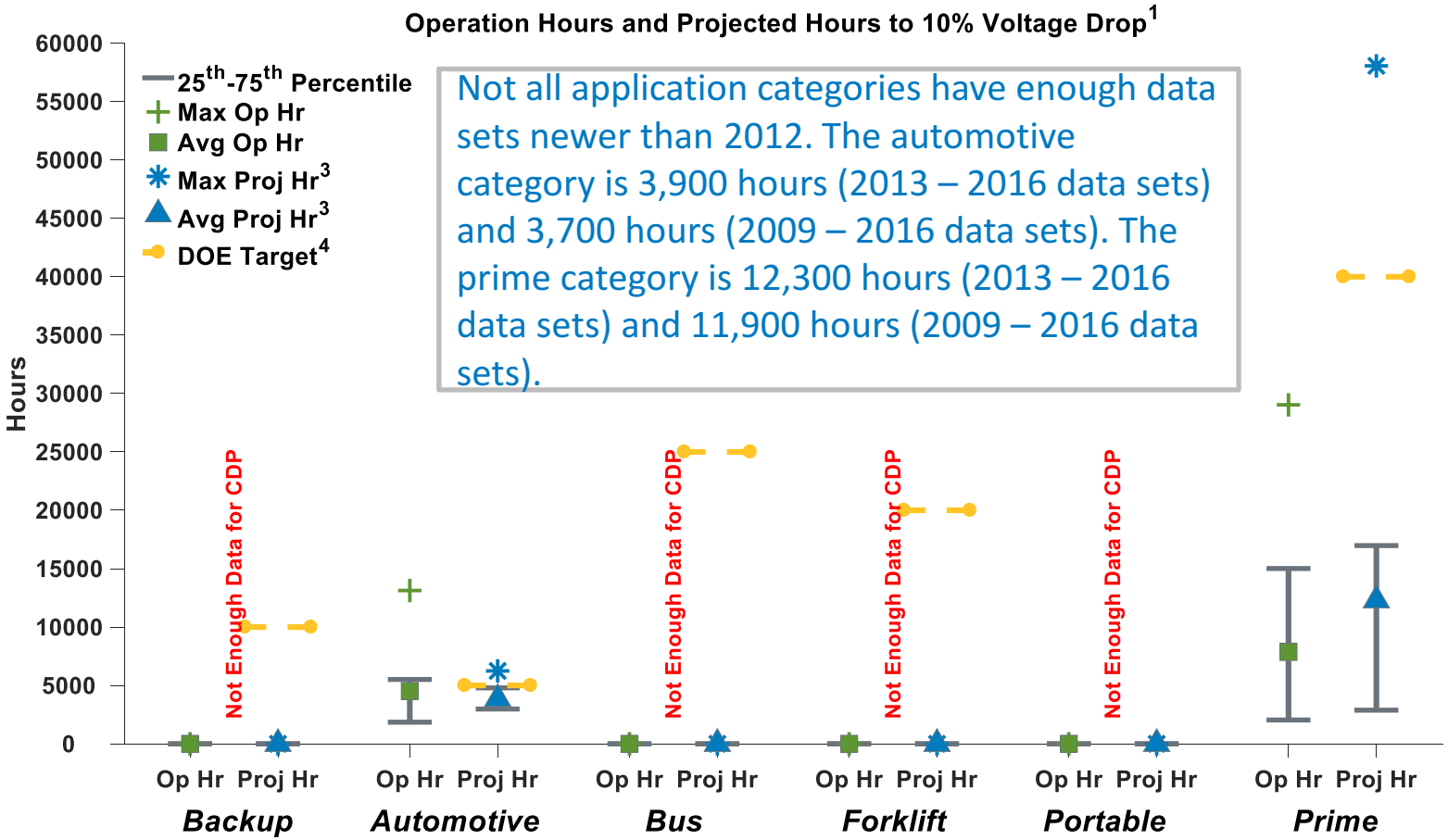
Created: Apr-20-17 11:48 AM | Data Range: 2009Q1-2016Q4

(1) The DOE 10% voltage degradation metric is used for assessing voltage degradation; it may not be the same as end-of-life criteria and does not address catastrophic failure modes.

(2) At least 13 fuel cell developers supplied data, including international. Analysis is updated periodically.

Updated

Accomplishment: Excluding Pre-2013 Data for Recent Results



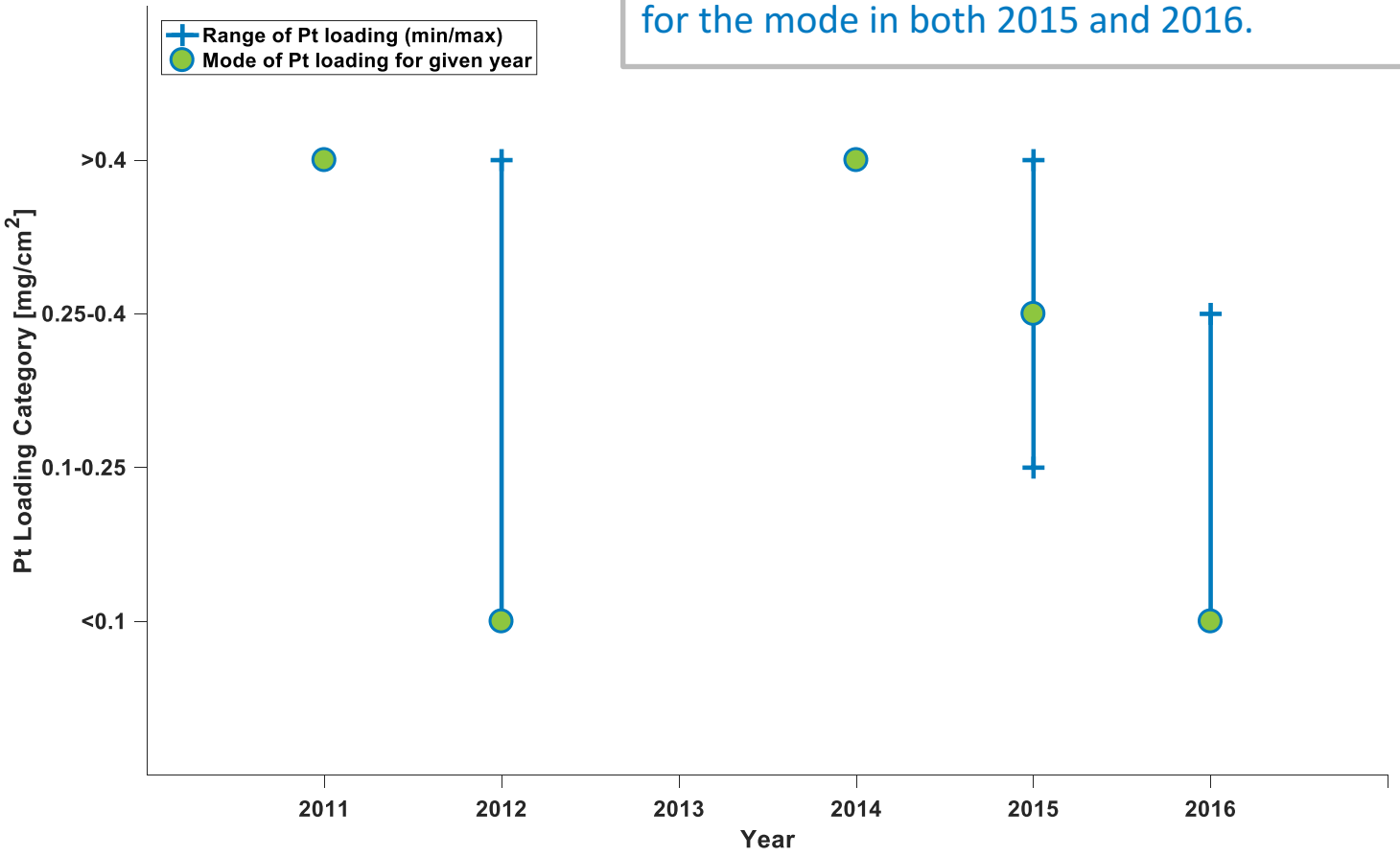
(1) Partial data from 2013-2016 only, full dataset includes least 19 U.S. and international fuel cell developers. See CDP-Lab-01 for full data set.
(2) PEMFC, DMFC & SOFC data from lab tested, full active area short stacks and systems with full stacks. Data generated from constant load, transient load, and accelerated testing between 2004 and early 2012.
(3) The DOE 10% voltage degradation metric is used for assessing voltage degradation; it may not be the same as end-of-life criteria and does not address catastrophic failure modes.
(4) DOE targets are for real-world applications; refer to Hydrogen, Fuel Cells, & Infrastructure Technologies Program Plan.

NREL cdp_lab_21
Created: Apr-20-17 11:49 AM | Data Range: 2009Q1-2016Q4

New

Accomplishment: Platinum Loading Trend

The platinum loading per square centimeter is decreasing on the data sets analyzed, per the trend for the mode in both 2015 and 2016.



NREL cdp_lab_20

1. Platinum loading is plotted in the year when lab operation started and aggregates all applications, configurations and test conditions for data sets that provided loading data.

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Durability was not collected in FY14, which is why there is not data graphed in 2013.

New

2016 AMR feedback

- "Legacy data should be limited or eliminated to ensure that it does not dilute the performance reporting of current technology."
  - We created a new CDP showing only data sets which span the last 4 years. To maintain proprietary information we are only publishing results for applications which include at least 3 data sets and 2 companies in a given year.
- "NREL should bin total platinum content in the ranges of >60 g, 30-60 g, 15-30 g, and <10 g."
  - We created a new CDP for platinum loading of analyzed data. Showing platinum loadings over time can provide insight into how costs may have changed. Furthermore relating this to durability over time, we may be able to show indirectly how costs and durability have been affected by recent R&D activities.
- "The current density of 1.5 A/cm2 should be added to the current density variation chart"
  - Done.
- "The project should start to distinguish different types of acceleration data in order to understand the difference in protocols and how they compare to duty cycles."
  - In-process analysis which would help us characterize the different accelerated test data and segment the results more effectively. We are coordinating with FC PAD to make this more meaningful.

Collaborations

- Multiple fuel cell developers voluntarily supplied data
  - 23 fuel cell developers contacted have supplied at least one dataset
  - Reasons for developers not providing data include concerns over voluntary proprietary data sharing, availability of data sets with high operation time that are a good fit to include in the analysis, and readily accessible data in the requested format
  - Data contributors are not identified yet because of limited data sets by application category
- Gathering PEMFC, DMFC, SOFC, and electrolyzer datasets
- Data sharing is completely voluntary
- Participation in DOE durability working group and presentation of status to fuel cell tech team
- Ongoing effort with fuel cell & electrolyzer developers to:
  - Include new data sets (particularly in the stationary category)
  - Update datasets already included if applicable
  - Include new fuel cell developers

Remaining Challenges and Barriers

- Voluntarily supplied data / Action – annual check on data
- Inconsistent availability of data / Action – annual check on data
- Legacy data impact on current, state-of-the-art durability projections / Action – rolling window of results
- Focus of developers on reducing cost (or other areas) may be seen as steady voltage durability over the years / Action - analyzing and reporting on the relationship between lowering cost and improving durability
- Requests for additional information relevant to durability is not addressed because that data isn't provided / Action – request on platinum loading

Proposed Future Work

- Continue status update on fuel cell & electrolyzer durability and system cost/price – cost/price and durability status update planned for FY18
- Continue cultivating existing collaborations and developing new collaborations with fuel cell developers

Accelerated Testing Data Mining

- In process – analysis to characterize various accelerated testing
- Categorization options include transients, start/stops, and temperature
- Compare with standard DOE accelerated stress tests
- Coordinating with FC PAD

Table 3.4.17 Electrocatalyst Cycle and Metrics

Cycle	Triangle sweep cycle: 50 mV/s between 0.6 V and 1.0 V; run polarization curve and ECSA at specified intervals. Single cell 25-50 cm^2
Number	30,000 cycles
Cycle time	16 s
Temperature	80°C
Relative Humidity	Anode/Cathode 100/100%
Fuel/Oxidant	Hydrogen/N_2 (H_2 at 200 sccm and N_2 at 75 sccm for a 50 cm^2 cell
Pressure	Atmospheric pressure

Metric	Frequency	Target
Catalytic Mass Activity[a]	At Beginning and End of Test minimum	≤40% loss of initial catalytic activity
Polarization curve from 0 to ≥1.5 A/cm^2 [b]	After 0, 1k, 5k, 10k, and 30k cycles	≤30 mV loss at 0.8 A/cm^2
ECSA/Cyclic Voltammetry[c]	After 10, 100, 1k, 3k, 10k, 20k and 30k cycles	≤40% loss of initial area

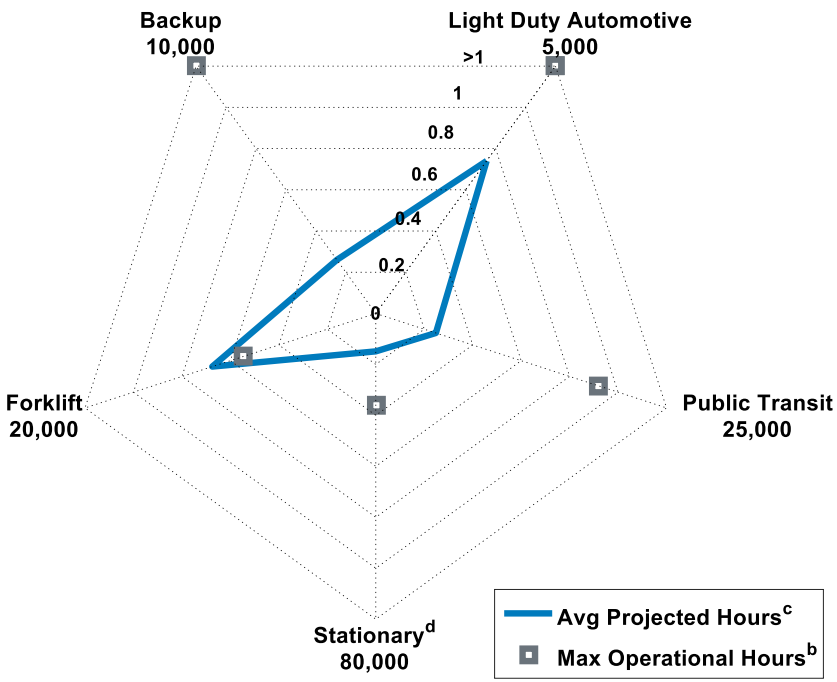
a. Mass activity in A/mg @ 150 kPa abs backpressure at 900 mV iR-corrected on H_2/O_2, 100% RH, 80°C, anode stoichiometry 2; cathode stoichiometry 9.5, normalized to initial mass of catalyst and measured before and after test (as per Gasteiger et al. Applied Catalysis B: Environmental, 56 (2005) 9-35). Measured ORR current may be corrected for H_2 crossover.

b. Polarization curve per protocol in Table 3.4.21.

c. Sweep from 0.05 to 0.6 V at 20 mV/s, 80°C, 100% RH.

FC Technology Status Summary - Durability

Application		2020 DOE Durability Target[a]	Lab Status - Ave Hrs to 10% Voltage Degradation[b]
Light Duty Automotive		5,000 Hours	3,700
Public Transit		25,000 Hours	6,200
Stationary	1-10 kW	0.3%/1,000 Hours	11,900
	100 kW - 3 MW	80,000 Hours	
Forklift		20,000 Hours - Target Under Review	13,500
Backup		10,000 Hours - Target Under Review	2,600



a. Fuel Cell Technolgies Office Multi-Year Research, Development, and Demonstration Plan (MYRDD) <https://energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22>
b. Current results are available at http://www.nrel.gov/hydrogen/images/cdp_lab_01.jpg (Updated 04/2017) or from on-road results (2016 Annual FCB results www.nrel.gov/docs/fy17osti/67097.pdf)
c. Results are a fraction of the 2020 targets in the MYRDD.
d. Stationary 100kW-3MW vs DOE target of 80,000 hrs.

NREL cdp_lab_19
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Summary

Relevance: Independent assessment of state-of-the-art fuel cell technology provides one location for fuel cell & electrolyzer durability status from leading developers with a uniform analysis and reporting method on a variety of proprietary data.

Approach: Leverage NFCTEC and prioritized industry collaborations.

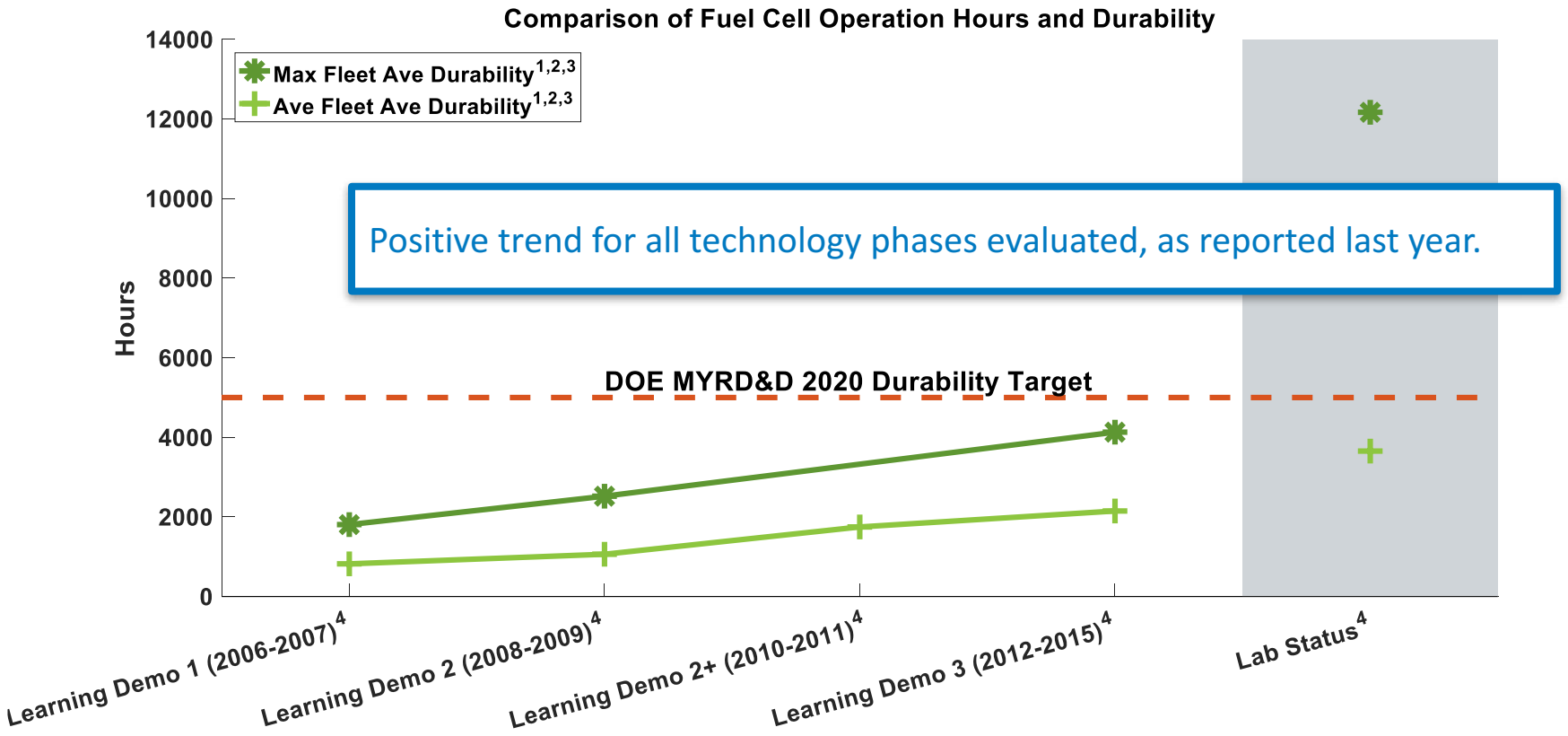
Accomplishments: Updated seventh annual results for six applications, including electrolysis, and included new details based on metadata and durability trends over time and international developers. The data are fully integrated into NRELFAT and an online interface provides information on the project, connection for interested collaborators, and all publications. Improved project information material for details and benefits of participation.

Durability results are relatively steady of the past 4-5 years while the platinum loading is decreasing.

Collaborations and Future Work: Continue expanding analyzed data sets, included fuel cell developers, and results.

Technical Back-Up Slides

Accomplishment – Comparison with On-Road FCEV voltage durability



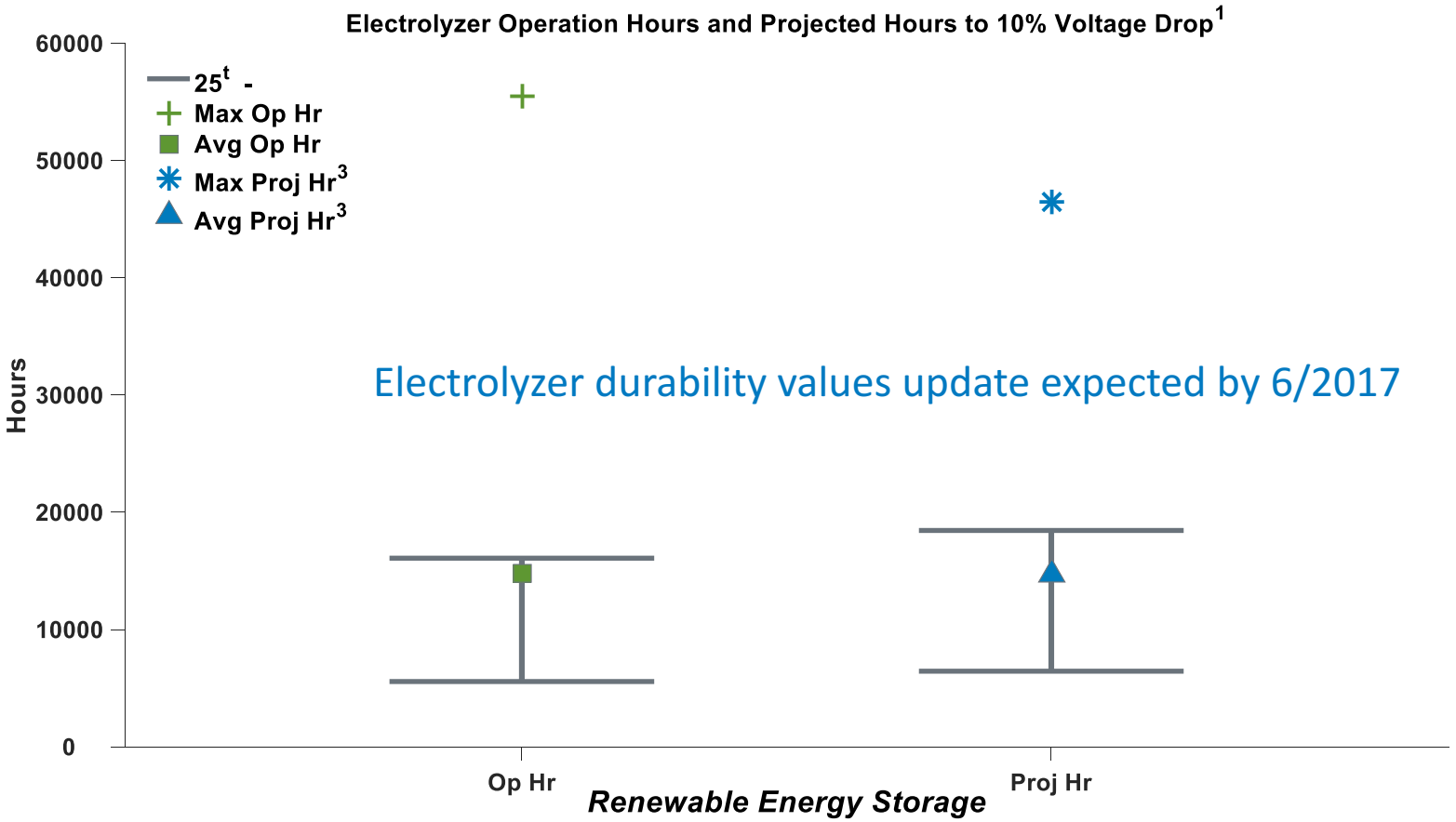
1. Durability based on voltage degradation to 10% lower than beginning of life voltage. 10% voltage drop level is a DOE metric for assessing fuel cell durability.
2. Projections using on-road data are calculated at approximately 55%-65% rated stack current.
3. 10% voltage drop is NOT an indication of an OEM's end-of-life criteria and projections do not address catastrophic stack failure.
4. Maximum operational hours: 2,375 (LD1); 1,200 (LD2); 5,648 (Current FCEV Analysis); 13,129 (Lab Status); Maximum operational hours not reported in Learning Demonstration 2 continuation (LD2+) (2010-2011).

NREL cdp_lab_03

Created: May-05-17 3:54 PM | Data Range: 2004Q1-2016Q4

Updated – only lab

Accomplishment – Electrolyzer Voltage Durability



(1) At least 3 electrolyzer test labs supplied data. Analysis is updated periodically.
(2) Full active area short stacks and systems with full stacks. Data generated from constant load, transient load, and accelerated testing between 2003 and early 2015.
(3) The DOE 10% voltage degradation metric is used for assessing voltage degradation; it may not be the same as end-of-life criteria and does not address catastrophic failure modes.

NREL cdp_lab_18
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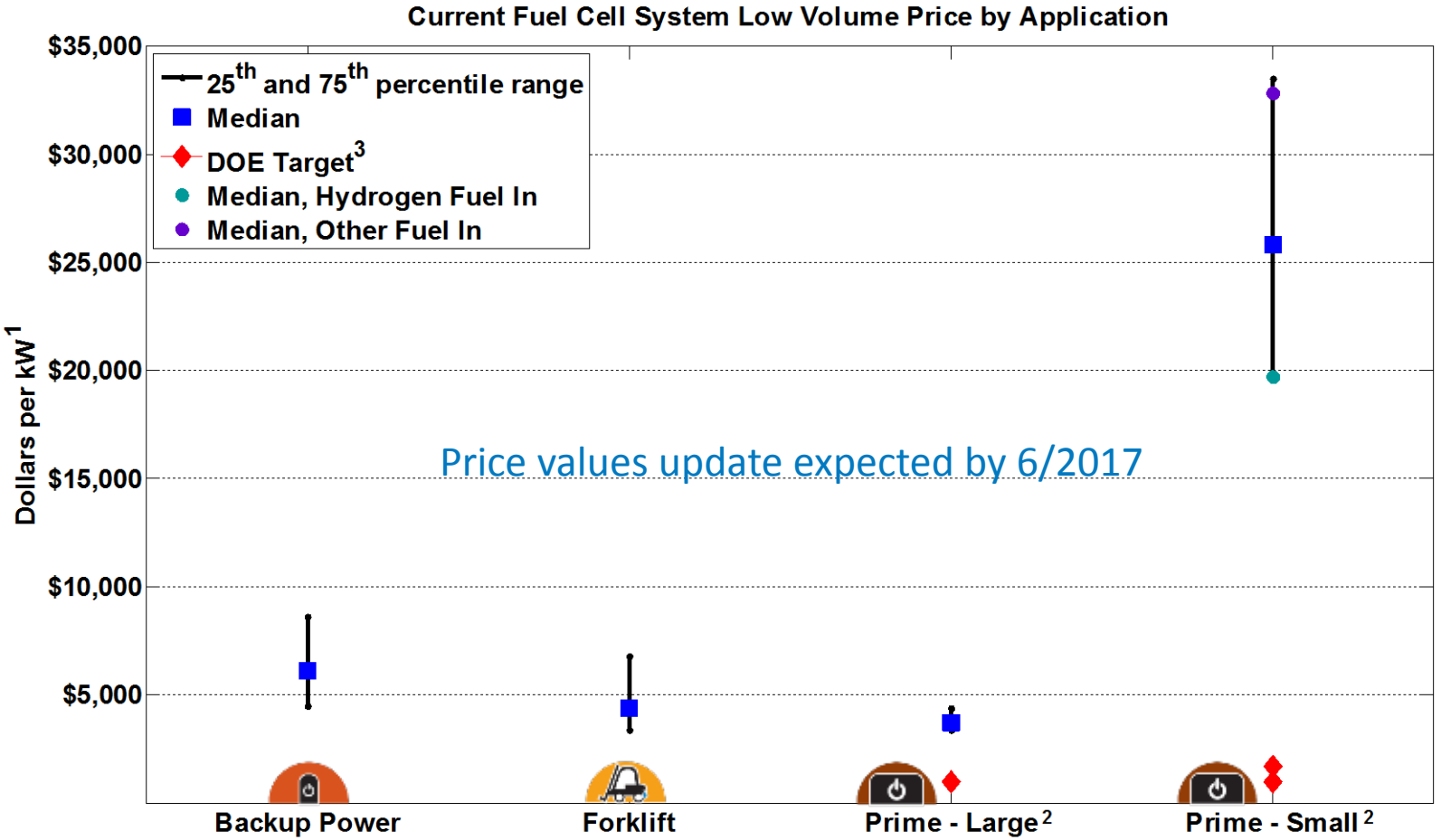
Low Volume Price of Current Fuel Cell Systems



1. Data (in 2013 dollars without incentives) sources include public information, ARRA deployments, and fuel cell developers (voluntarily supplied). Includes over 35 different data points from more than 7 domestic and international fuel cell developers.
2. Prime power data includes multiple system sizes, types, and fuels. Small prime is < 11 kW.
3. Based on DOE MYRDD Fuel Cell section tables 3.4.5 and 3.4.6.

NREL cdp_lab_15
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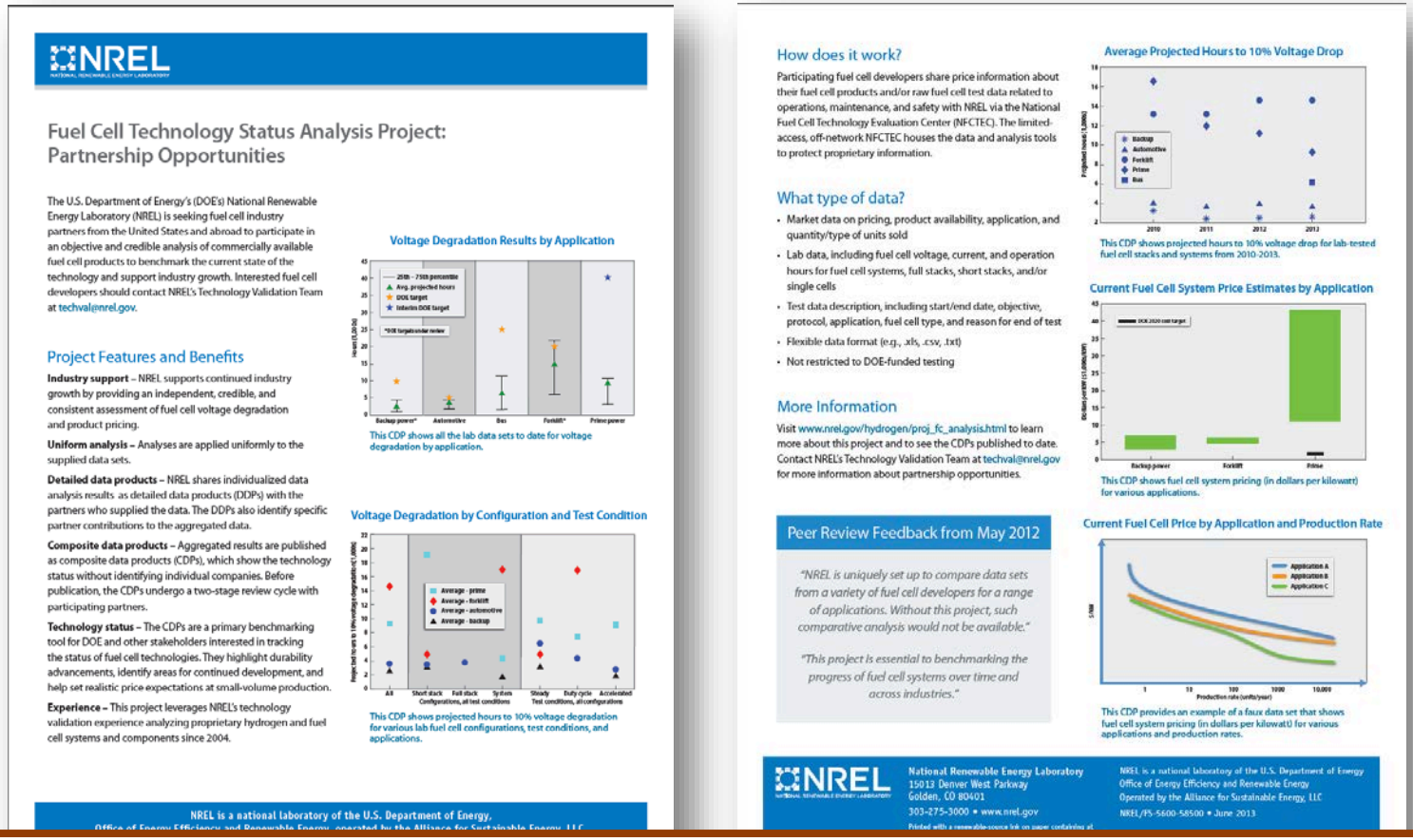
Pamphlet with Participation Details and Benefits



Fuel Cell Technology Status Analysis Project: Partnership Opportunities

The U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) is seeking fuel cell industry partners from the United States and abroad to participate in an objective and credible analysis of commercially available fuel cell products to benchmark the current state of the technology and support industry growth. Interested fuel cell developers should contact NREL's Technology Validation Team at techval@nrel.gov.

Project Features and Benefits

Industry support – NREL supports continued industry growth by providing an independent, credible, and consistent assessment of fuel cell voltage degradation and product pricing.

Uniform analysis – Analyses are applied uniformly to the supplied data sets.

Detailed data products – NREL shares individualized data analysis results as detailed data products (DDPs) with the partners who supplied the data. The DDPs also identify specific partner contributions to the aggregated data.

Composite data products – Aggregated results are published as composite data products (CDPs), which show the technology status without identifying individual companies. Before publication, the CDPs undergo a two-stage review cycle with participating partners.

Technology status – The CDPs are a primary benchmarking tool for DOE and other stakeholders interested in tracking the status of fuel cell technologies. They highlight durability advancements, identify areas for continued development, and help set realistic price expectations at small-volume production.

Experience – This project leverages NREL's technology validation experience analyzing proprietary hydrogen and fuel cell systems and components since 2004.

Voltage Degradation Results by Application

This CDP shows all the lab data sets to date for voltage degradation by application.

Voltage Degradation by Configuration and Test Condition

This CDP shows projected hours to 10% voltage degradation for various lab fuel cell configurations, test conditions, and applications.

NREL is a national laboratory of the U.S. Department of Energy.

How does it work?

Participating fuel cell developers share price information about their fuel cell products and/or raw fuel cell test data related to operations, maintenance, and safety with NREL via the National Fuel Cell Technology Evaluation Center (NFCTEC). The limited-access, off-network NFCTEC houses the data and analysis tools to protect proprietary information.

What type of data?

- Market data on pricing, product availability, application, and quantity/type of units sold
- Lab data, including fuel cell voltage, current, and operation hours for fuel cell systems, full stacks, short stacks, and/or single cells
- Test data description, including start/end date, objective, protocol, application, fuel cell type, and reason for end of test
- Flexible data format (e.g., .xls, .csv, .txt)
- Not restricted to DOE-funded testing

More Information

Visit www.nrel.gov/hydrogen/proj_fc_analysis.html to learn more about this project and to see the CDPs published to date. Contact NREL's Technology Validation Team at techval@nrel.gov for more information about partnership opportunities.

Peer Review Feedback from May 2012

"NREL is uniquely set up to compare data sets from a variety of fuel cell developers for a range of applications. Without this project, such comparative analysis would not be available."

"This project is essential to benchmarking the progress of fuel cell systems over time and across industries."

Average Projected Hours to 10% Voltage Drop

This CDP shows projected hours to 10% voltage drop for lab-tested fuel cell stacks and systems from 2010-2013.

Current Fuel Cell System Price Estimates by Application

This CDP shows fuel cell system pricing (in dollars per kilowatt) for various applications.

Current Fuel Cell Price by Application and Production Rate

This CDP provides an example of a faux data set that shows fuel cell system pricing (in dollars per kilowatt) for various applications and production rates.

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC
NREL/PS-5600-58500 • June 2013

The U.S. Department of Energy's National Renewable Energy Laboratory is seeking fuel cell industry partners from the United States and abroad to participate in an objective and credible analysis of commercially available fuel cell product cost/price and durability data to benchmark the current state of the technology and support industry growth.