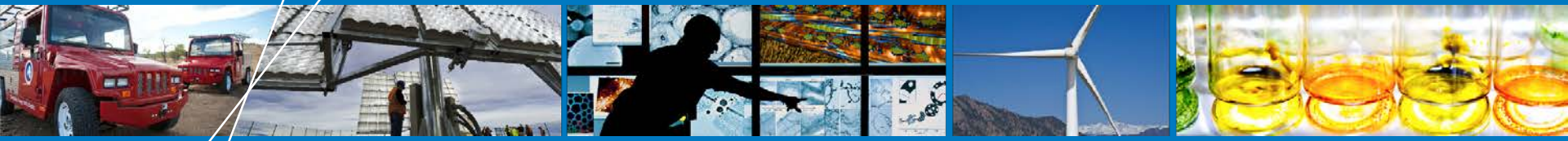
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Fuel Cell Technology Status: Degradation



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National Renewable Energy Laboratory
June 8, 2016

Project ID FC-081

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

Overview

Timeline and Budget

- **Project[1] start date: July 2009**
- **FY15 DOE funding: $85k**
- **FY16 planned DOE funding: $100k**
- **Total DOE funds received to date: $735k**

Partners

- **U.S. and international fuel cell 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
Stationary 100 kW – 3 MW	80,000 Hours
Electrolysis	TBD

[1] Project continuation and direction determined annually by DOE

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

Relevance

Benchmark state-of-the-art durability

- Develop snapshot of state-of-the-art fuel cell and electrolysis durability
- Uniformly apply analysis method to **developers' voluntarily supplied data from lab testing (technology readiness level ~ 3 – 5)**
- Obtain independent assessment and status of state-of-the-art fuel cell technology

Leverage analysis experience

- Utilize analysis methods, experience, and data from fuel cell field demonstrations (e.g., DOE's FCEV validation project)
- Compare lab and field data

Collaborate with key fuel cell developers

- Provide feedback to fuel cell developers
- Benchmark fuel cell durability

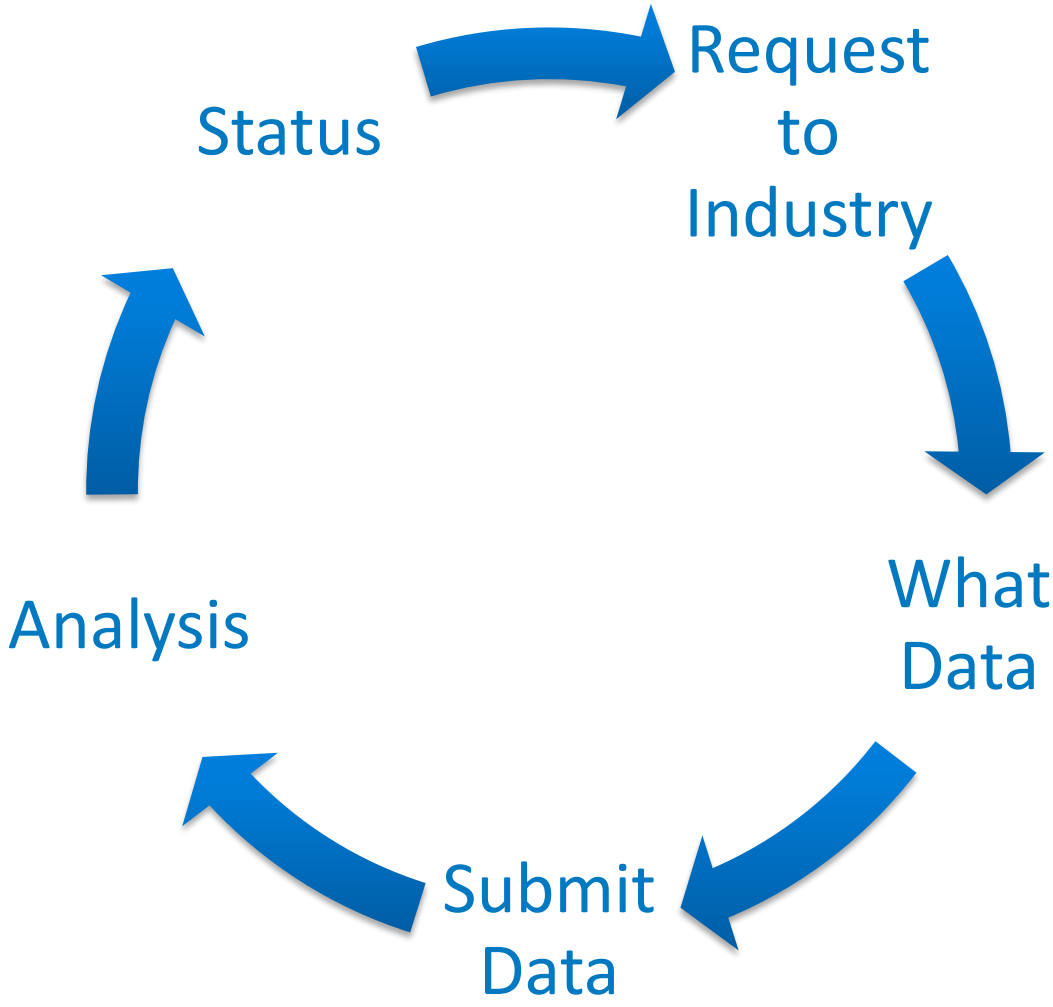
FY16 Objectives

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

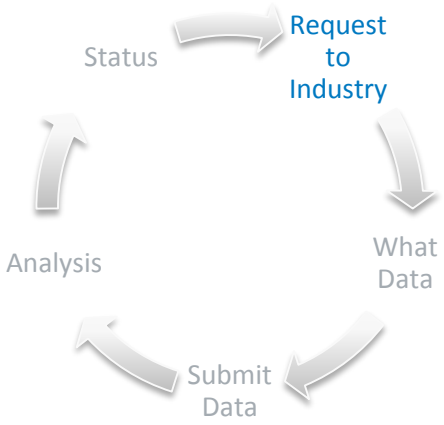
Barrier/Impact

- 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)

Approach – State-of-the-art Lab Fuel Cell & Electrolysis Voltage Degradation Annual Benchmarking



Approach – Data Request



Request to Industry

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

Sample Email Request

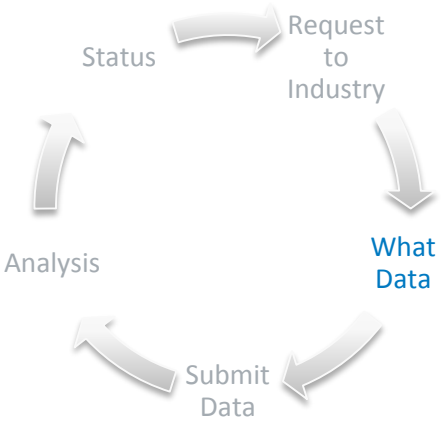
You are receiving this email because you have been identified as a leading fuel cell developer and a key participant for a fuel cell technology status benchmarking project by the National Renewable Energy Laboratory (NREL). This is one of NREL's technology validation projects where the results are referenced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

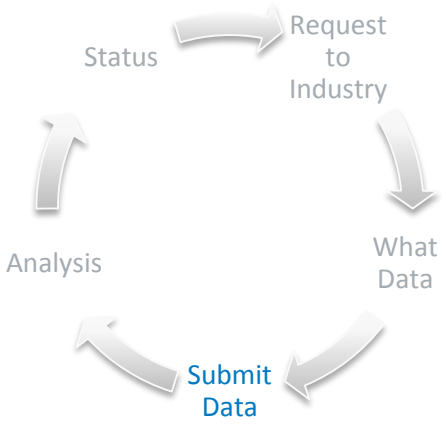
- Existing data from industry
- Voluntarily supplied
- Technology Readiness Level ~ 3 – 5
- Voltage, current, hours, metadata, market

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

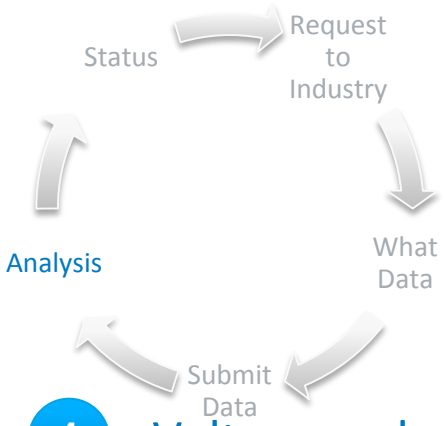
- Industry selected data sent to NFCTEC
- Data from variety of configurations and test protocols
- No specific test requirements, other than a high number of hours (e.g. > 1,000 hours)
- Fuel cell technologies include Polymer Electrolyte Membrane (PEM), Solid Oxide (SO), and Direct Methanol (DM), Electrolysis

Fuel Cell/Electrolyzer Technology Status Data Supply

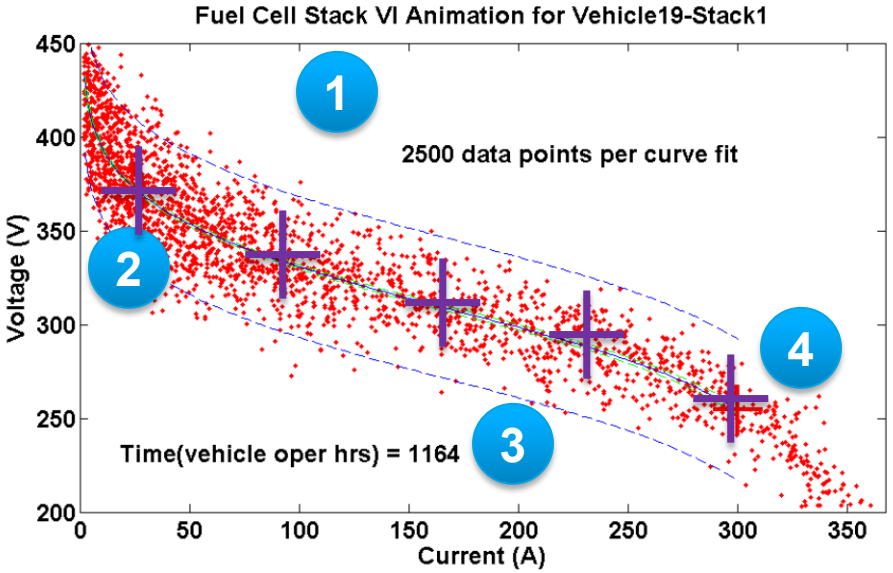
Voluntarily supplied from fuel cell developers
Durability – voltage, current, and hours minimum data needed
Test – time frame, objective, protocol, application, and type
Market – system price, availability, and application

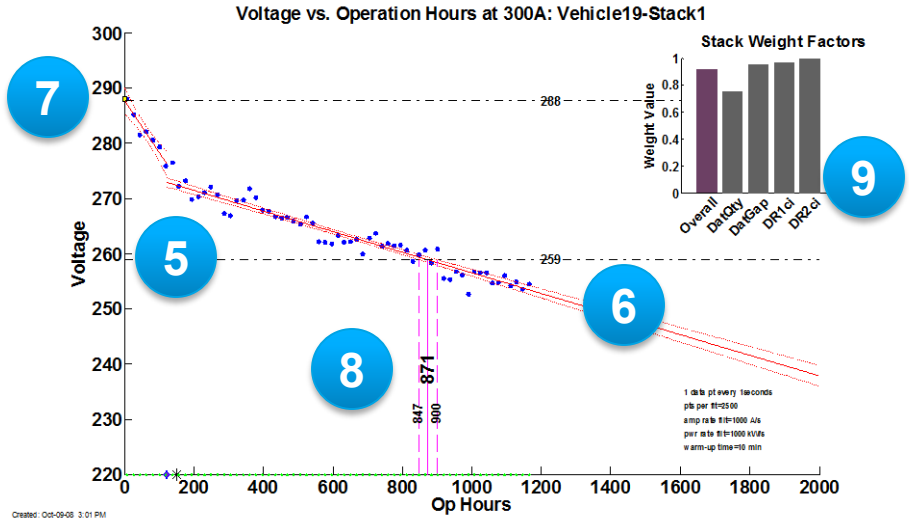
National Fuel Cell Technology Evaluation Center

Approach – Data Analysis



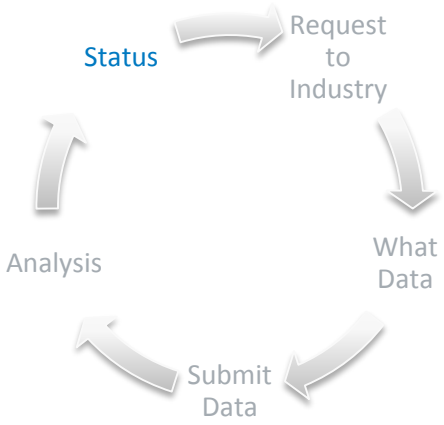
Analysis – EXAMPLE DATA



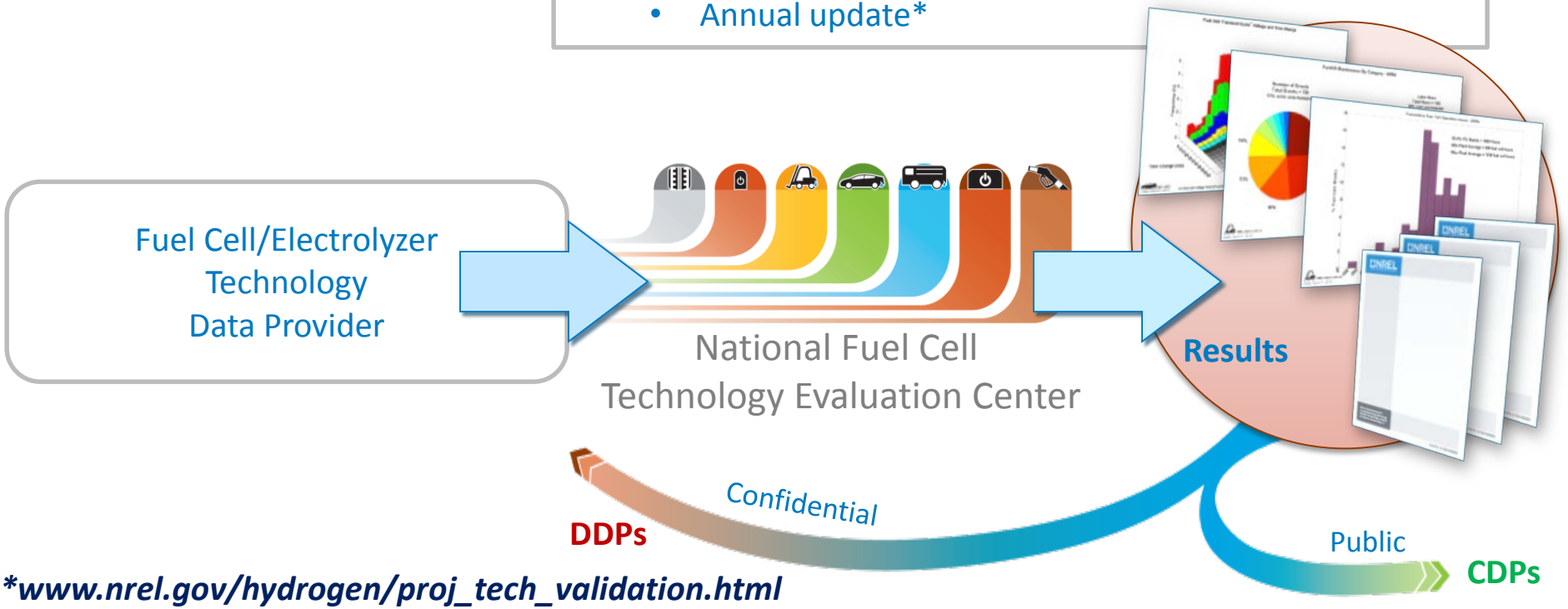


1. Voltage and current data
2. Apply polarization fit
3. Corresponding operation hour
4. Voltages from polarization fit at set currents
5. Fit voltage and operation data
6. Degradation linear fit
7. Y-intercept beginning of life voltage
8. Record operation hour when fit crosses 10% nominal voltage drop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



www.nrel.gov/hydrogen/proj_tech_validation.html

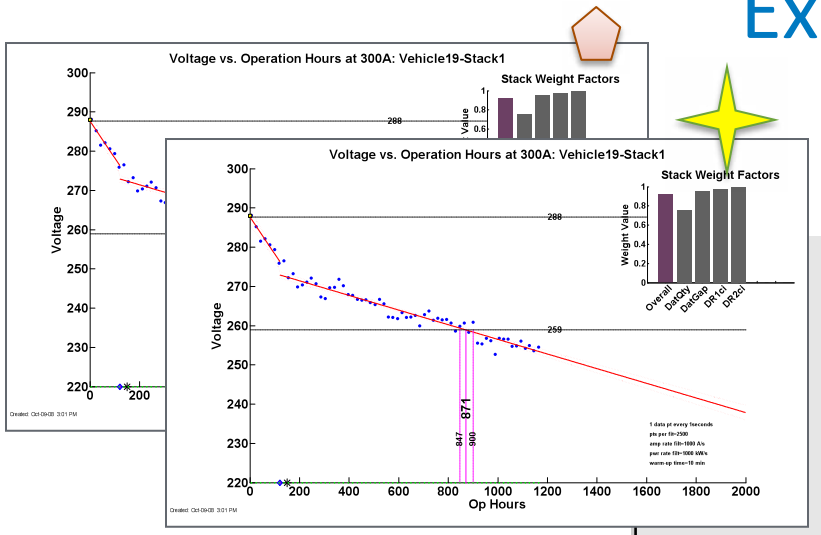
Approach: CDP and DDP Review

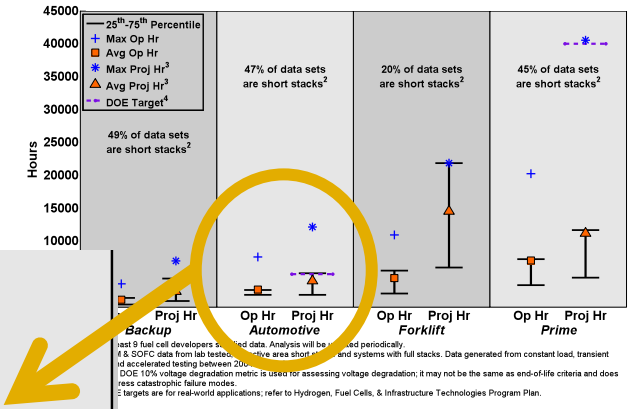
Data Process and Analysis

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





Op Hr Proj Hr

Automotive

Sample Data Set 1

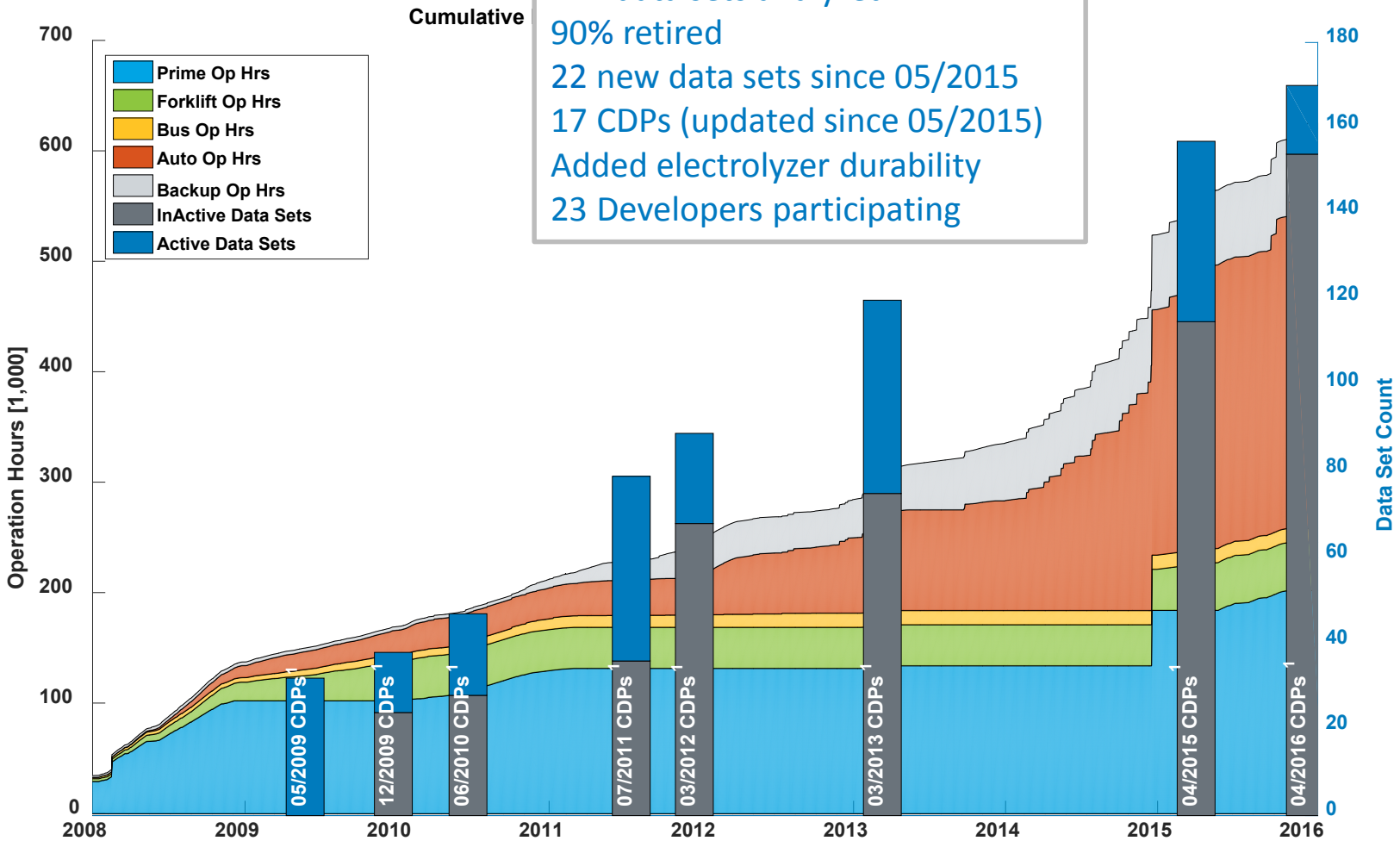
Sample Data Set 2

✓ **FY16 Milestone**

Analysis complete and updated results published by 04/2016

Accomplishments: Data Set Count and Operation Hours

05/2016 CDPs include
174 data sets analyzed
90% retired
22 new data sets since 05/2015
17 CDPs (updated since 05/2015)
Added electrolyzer durability
23 Developers participating



NREL cdp_lab_04
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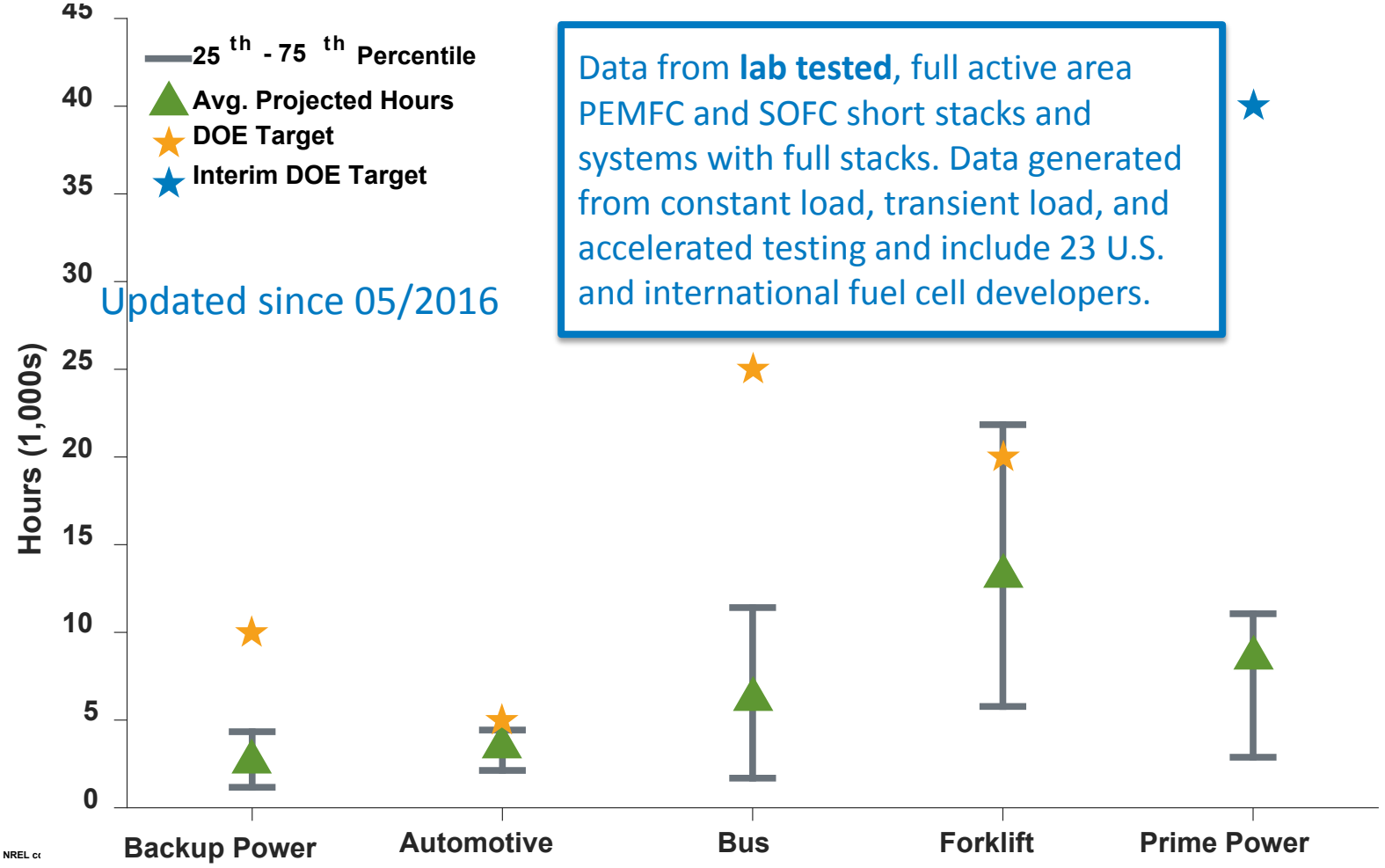
1) Data set count at publication of a CDP set - where a data set represents a short stack, full stack, or system test data.

Updated

Accomplishments: Voltage Degradation Results by Application

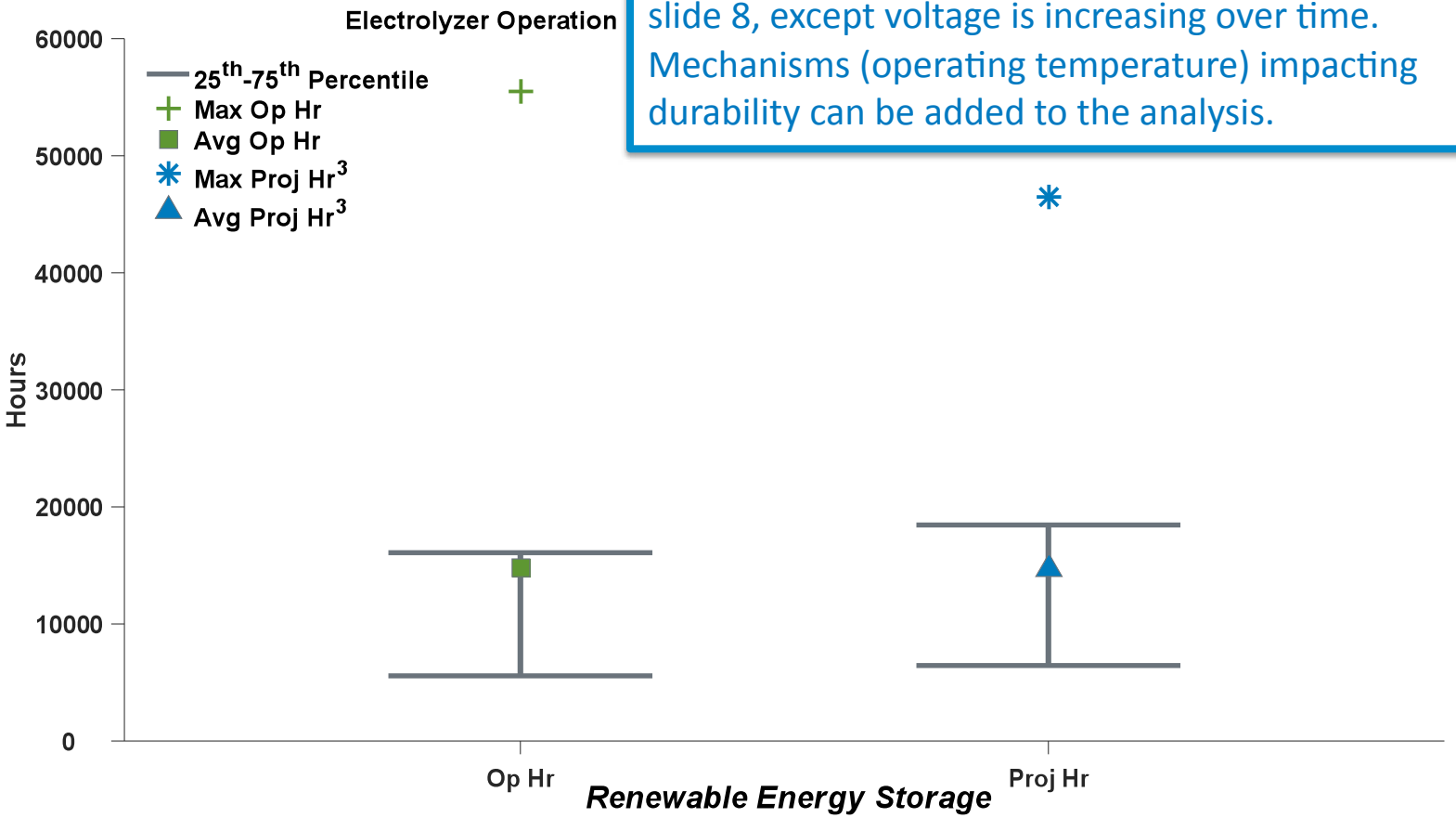
The average projected times (hrs) to 10% voltage drop are **2,600**, **3,500**, **6,200**, **13,200**, and **8,600** for **backup power**, **automotive**, **bus**, **forklift**, and **stationary** applications, respectively.



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 – Electrolyzer Voltage Durability

Added capability to study electrolyzer voltage degradation. Method similar to the process described in slide 8, except voltage is increasing over time. Mechanisms (operating temperature) impacting durability can be added to the analysis.



(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.

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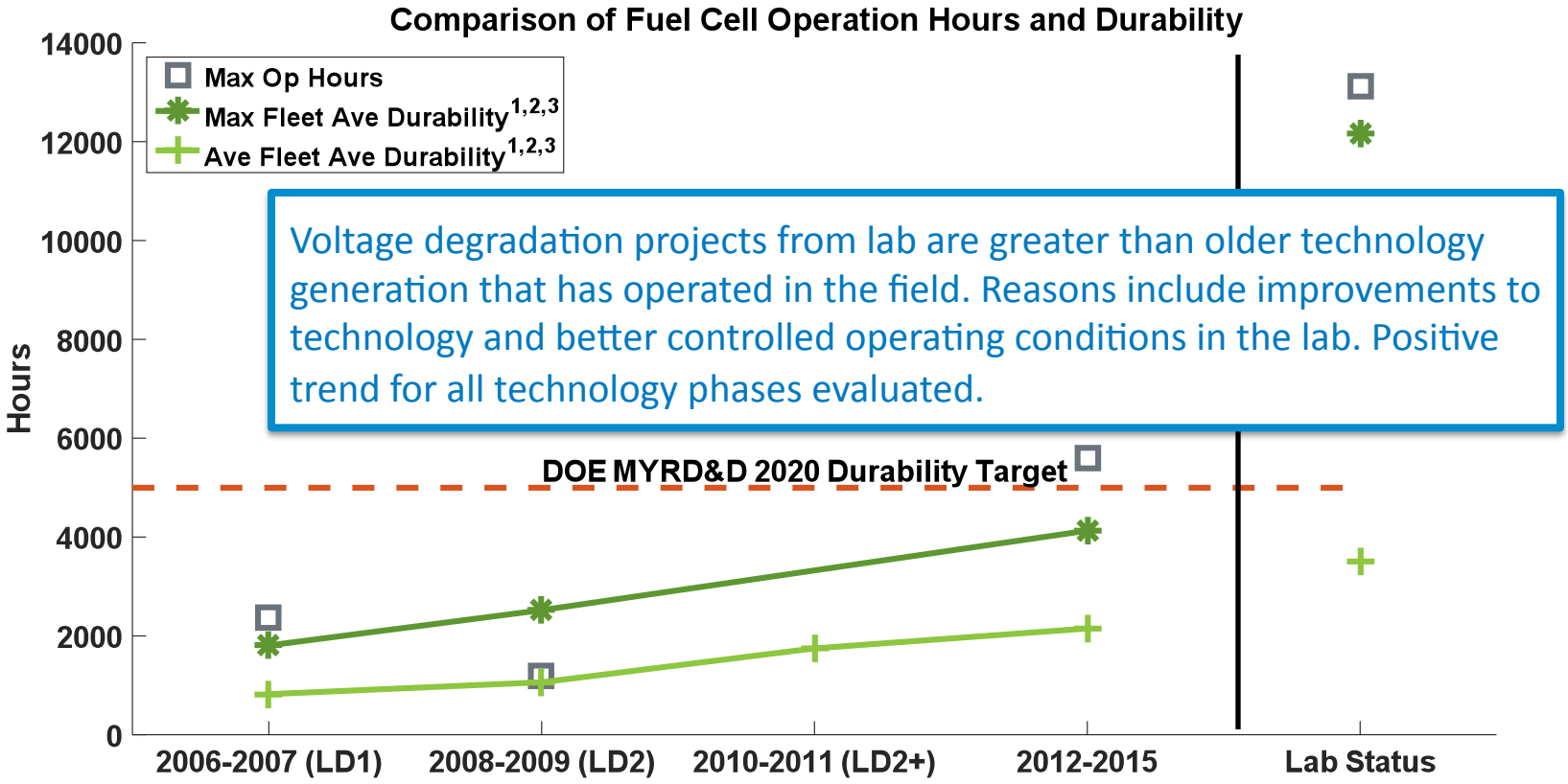
New

Accomplishment – Comparison with On-Road FCEV voltage durability



Voltage degradation projects from lab are greater than older technology generation that has operated in the field. Reasons include improvements to technology and better controlled operating conditions in the lab. Positive trend for all technology phases evaluated.

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. Percent increases are calculated relative to Learning Demonstration 1 (LD1) (2006-2007).
5. Maximum operational hours not reported in Learning Demonstration 2 continuation (LD2+) (2010-2011).

NREL cdp_lab_03
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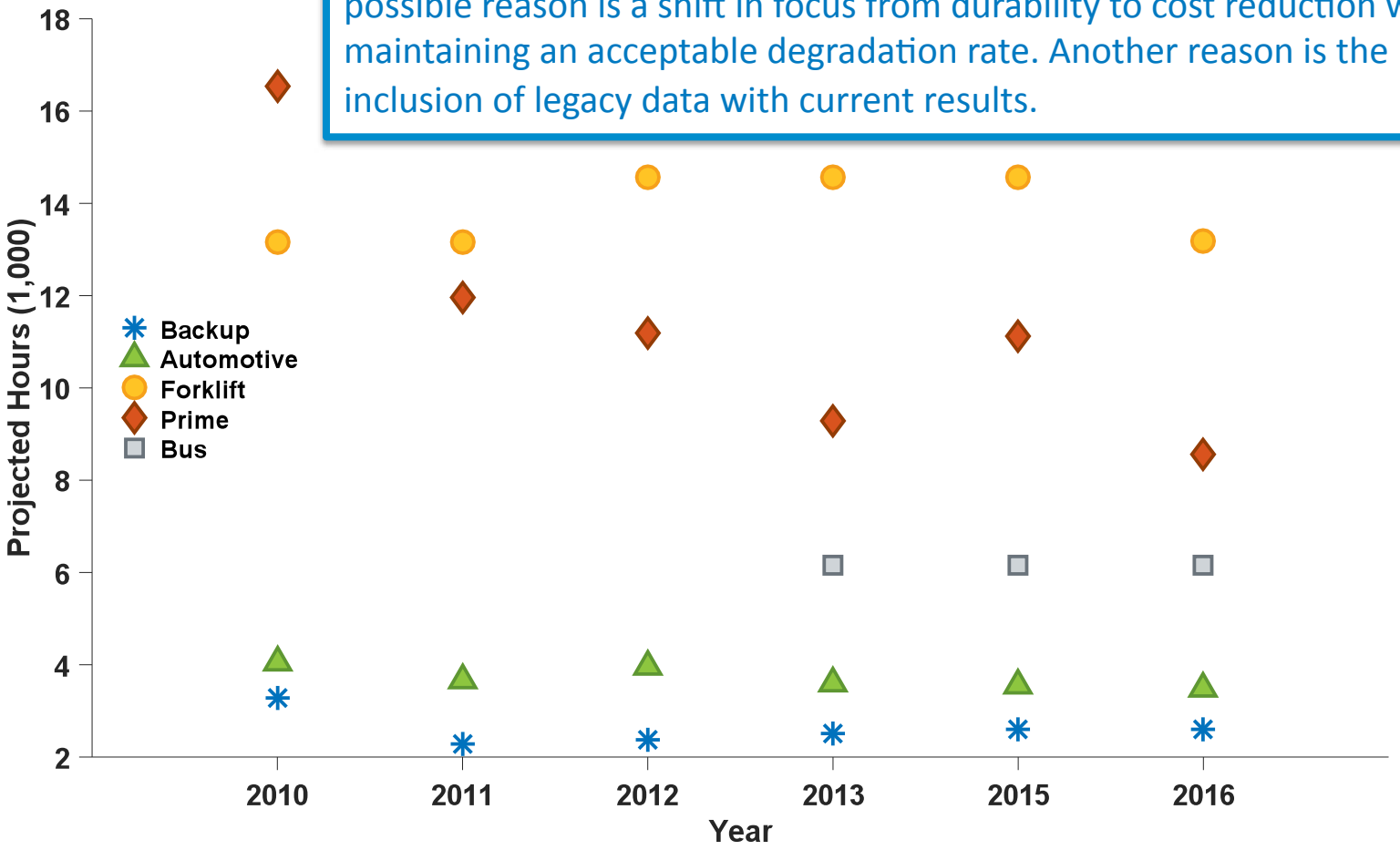
Updated

Accomplishment – Voltage degradation trend over time

Stabilized voltage durability projections over the years of analysis. A possible reason is a shift in focus from durability to cost reduction while maintaining an acceptable degradation rate. Another reason is the inclusion of legacy data with current results.



NREL cdp_lab_16

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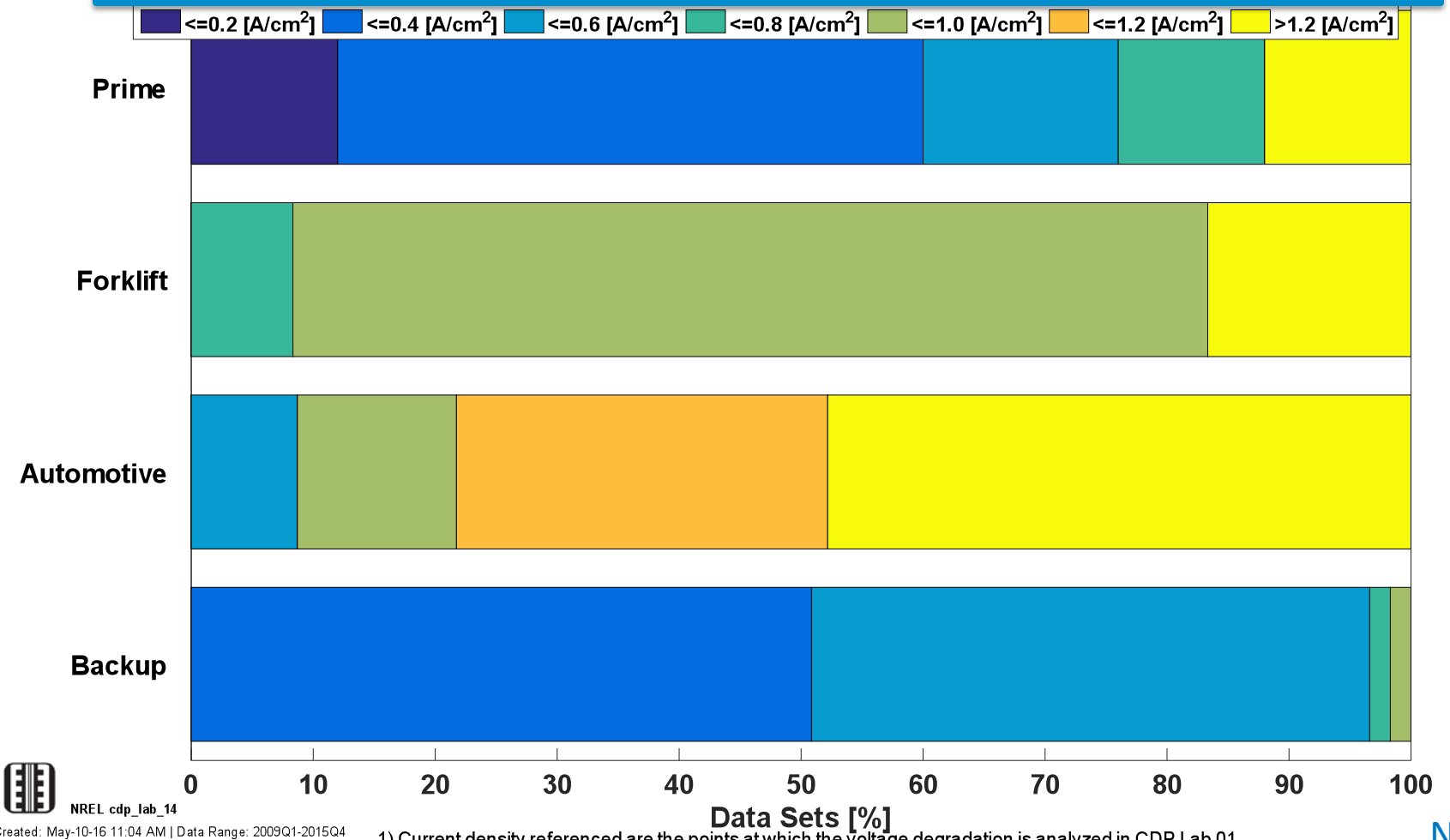
(1) The DOE 10% voltage degradation metric is used for assessing voltage degradation; it may not be the same as end-of-life criteria and does not address catastrophic failure modes.

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

Updated

Accomplishment – Current Density Variation between Data

Current density variation dependent on developer selected test protocols and objectives. A future comparison could be the study of voltage degradation at one chosen current density for all data sets within a category or type. The current density point used for the aggregated durability results are based on individual designs and data may not be available at multiple current densities.



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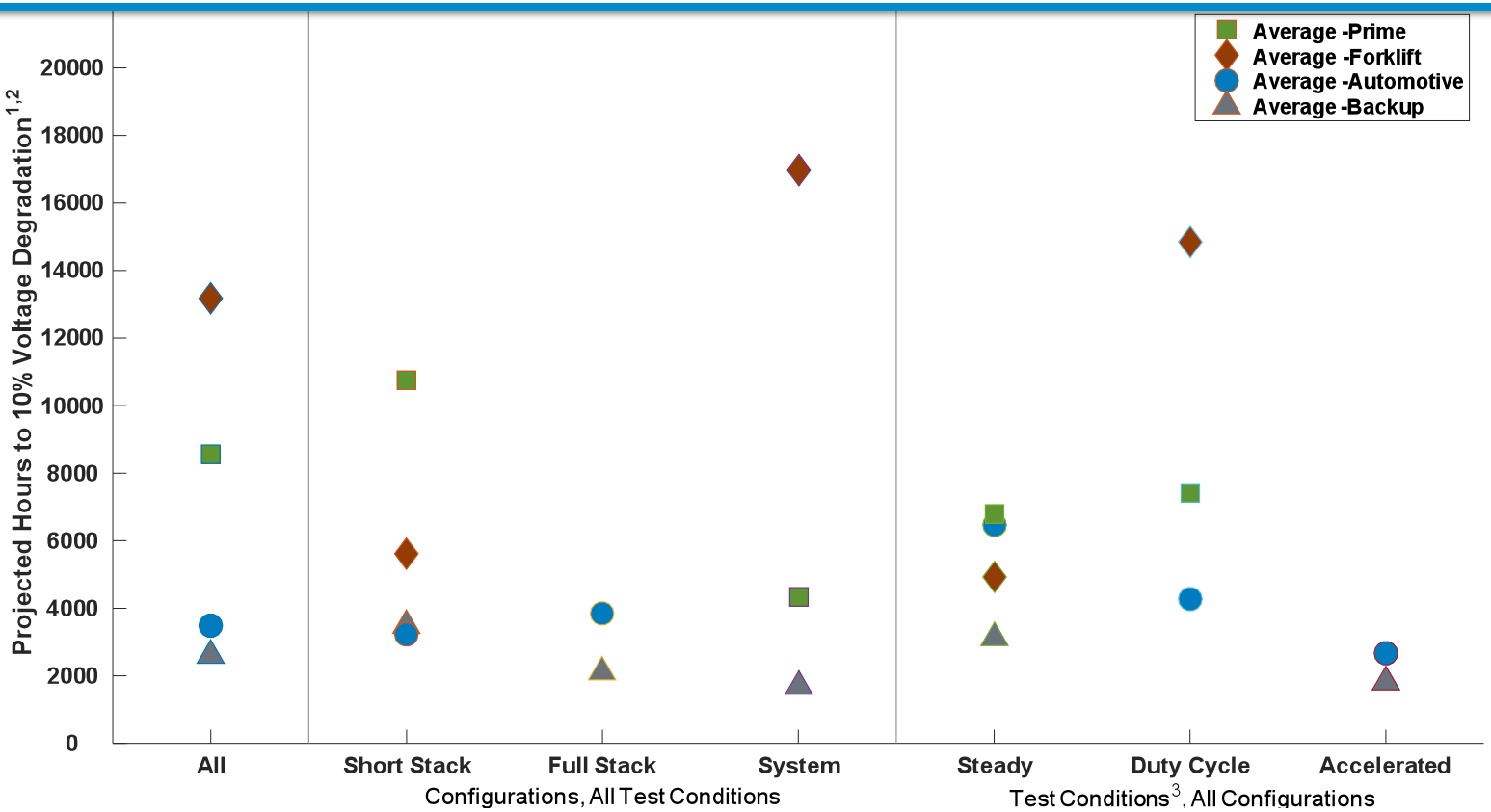
1) Current density referenced are the points at which the voltage degradation is analyzed in CDP Lab 01

New

Accomplishments: Voltage Degradation by Configuration and Test Condition

Grouping by configuration and test condition is important because of influences on degradation projections. Trend for the automotive data sets by test conditions is as expected. Other trends (e.g. system durability better than short stack) may be based on other factors (e.g. generation)



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

NREL cdp_lab_08

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2015 AMR feedback

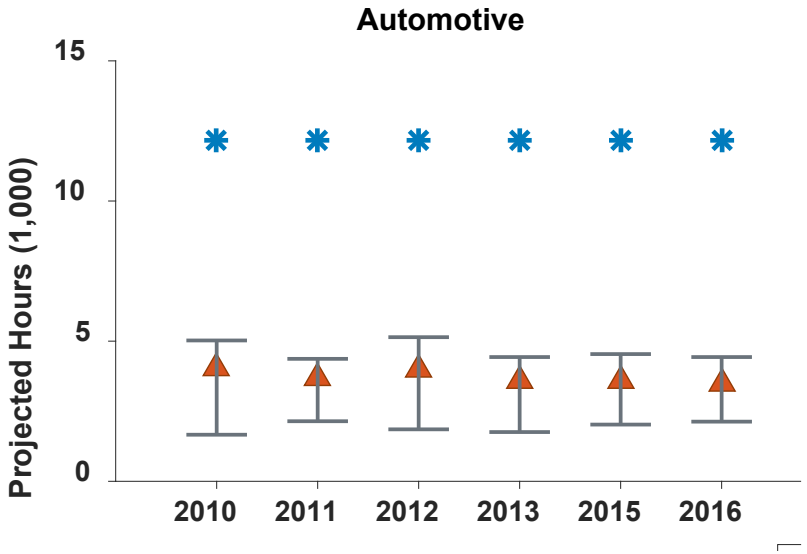
- **This analysis is not so useful unless the performance and durability statistics are shown with technical information such as fuel cell system design/materials/system architectures. Getting meaningful technical information from fuel cell developers on a voluntary basis seems to be a limitation.**
  - This is a challenge for this project. The team is working with DOE to increase the quality and type of data provided. This is in progress via DOE industry point of contact lists, additional (or optional) metadata requests, and included this as a requirement for applicable DOE awards.
- **Electrolyzer data will be very useful now that the focus in the fuel cell field has shifted to include the supply of hydrogen.**
  - An aggregated result of electrolyzer voltage durability is included for the first time.
- **The need for benchmarking is high. However, any analysis of performance and durability without technical information about design/materials/system architecture is not useful. Data acquisition on a voluntary basis shows critical limitations. Actual benchmarking on these vehicles would be able to show performance and durability with detailed technical information. Collaboration with U.S. DRIVE Partnership Technical Team is expected.**
  - Fuel cell vehicle voltage durability is tracked and measured (see TV001) and compared with findings in this project. We do ask for materials/system info in the metadata ask but the partner does not usually provide it.
- **The data are grouped by application but not by technology. Information is not provided about the progress of each technology to meet the application needs. This is very important for DOE and commercial clients in technology selection.**
  - Noted. The major challenge in grouping results by technology is additional limitation of publishing results because technology may identify a participant.

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

- Legacy data impact on current, state-of-the-art durability projections
- Focus of developers on reducing cost (or other areas) may conflict with increasing voltage durability in these results
  - Analyzing and reporting on the relationship between lowering cost and improving durability



E.g. stable average durability projects for automotive and max projection >> current on-road durability

- Voluntarily supplied data
- Inconsistent availability of data and status reporting
- Requests for additional information relevant to durability is not addressed because that data isn't provided

Proposed Future Work

- Continue status update on fuel cell & electrolyzer durability and system cost/price – cost/price and durability status update planned for FY17
- Continue cultivating existing collaborations and developing new collaborations with fuel cell developers
- Publish a report on the durability and cost analysis method (9/2016)
- Correlate stack durability data with single cell durability data via DOE test protocols
- Support DOE in development of an electrolyzer durability target

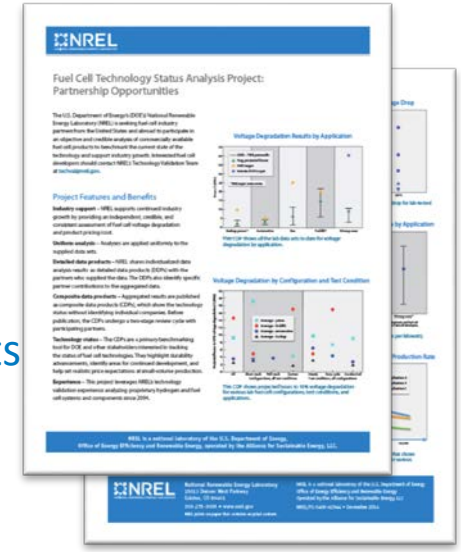
Summary

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

***Approach*:** Leverage NFCTEC and prioritized industry collaborations.

***Accomplishments*:** Updated sixth annual results for six applications, plus started 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.

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



Application	2020 Durability Target	Lab Status - Ave Hrs to 10% Voltage Degradation
Light Duty Automotive	5,000 Hours	3,500
Public Transit	25,000 Hours	6,200
Stationary 1-10kW	0.3%/1,000 Hours	8,600
Stationary 100 kW – 3 MW	80,000 Hours	
Forklift	20,000 Hours Target Under Review	13,200
Backup	10,000 Hours Target Under Review	2,600

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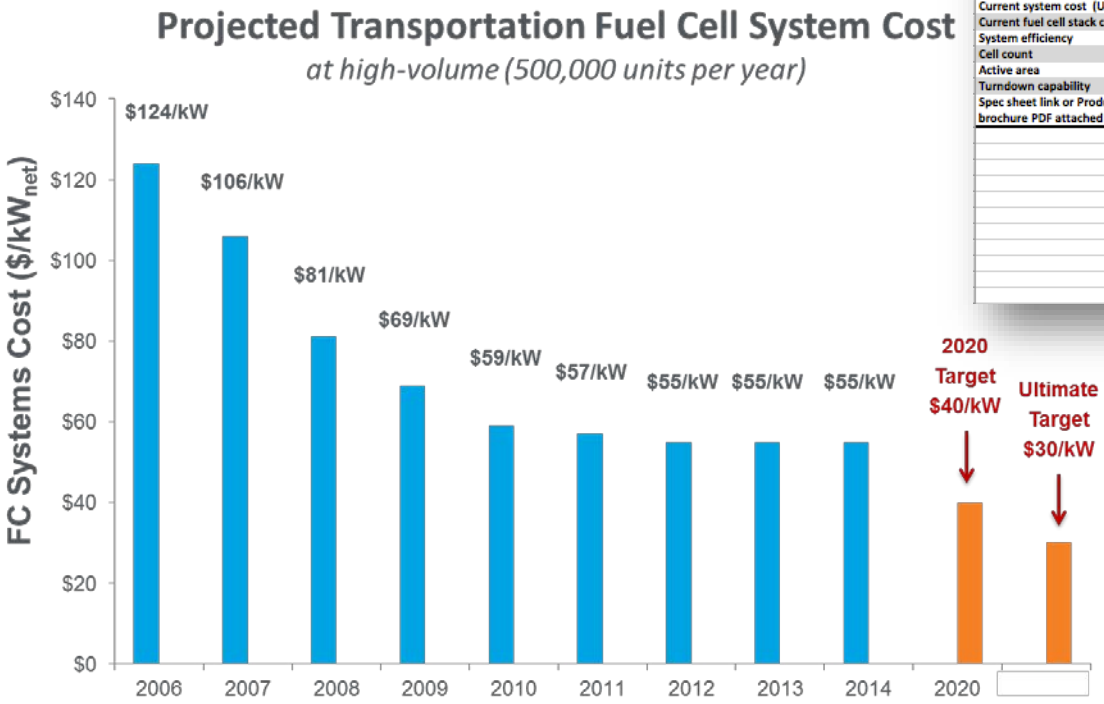
Technical Back-Up Slides

Approach: Current Status to Complement DOE Fuel Cell System Cost Based on Models for High Volume



Note: The information you provide here will be shared with the NREL National Fuel Cell Technology Evaluation Center for independent analysis and may be published as composite data products after a 2 stage review and concurrence process with the data providers. The information will be treated as confidential.

Instructions -

Please fill in applicable requested information for each available product, with each product entered as a new column. Some information may have been filled in based on an internet search of your available product. Please correct as appropriate.

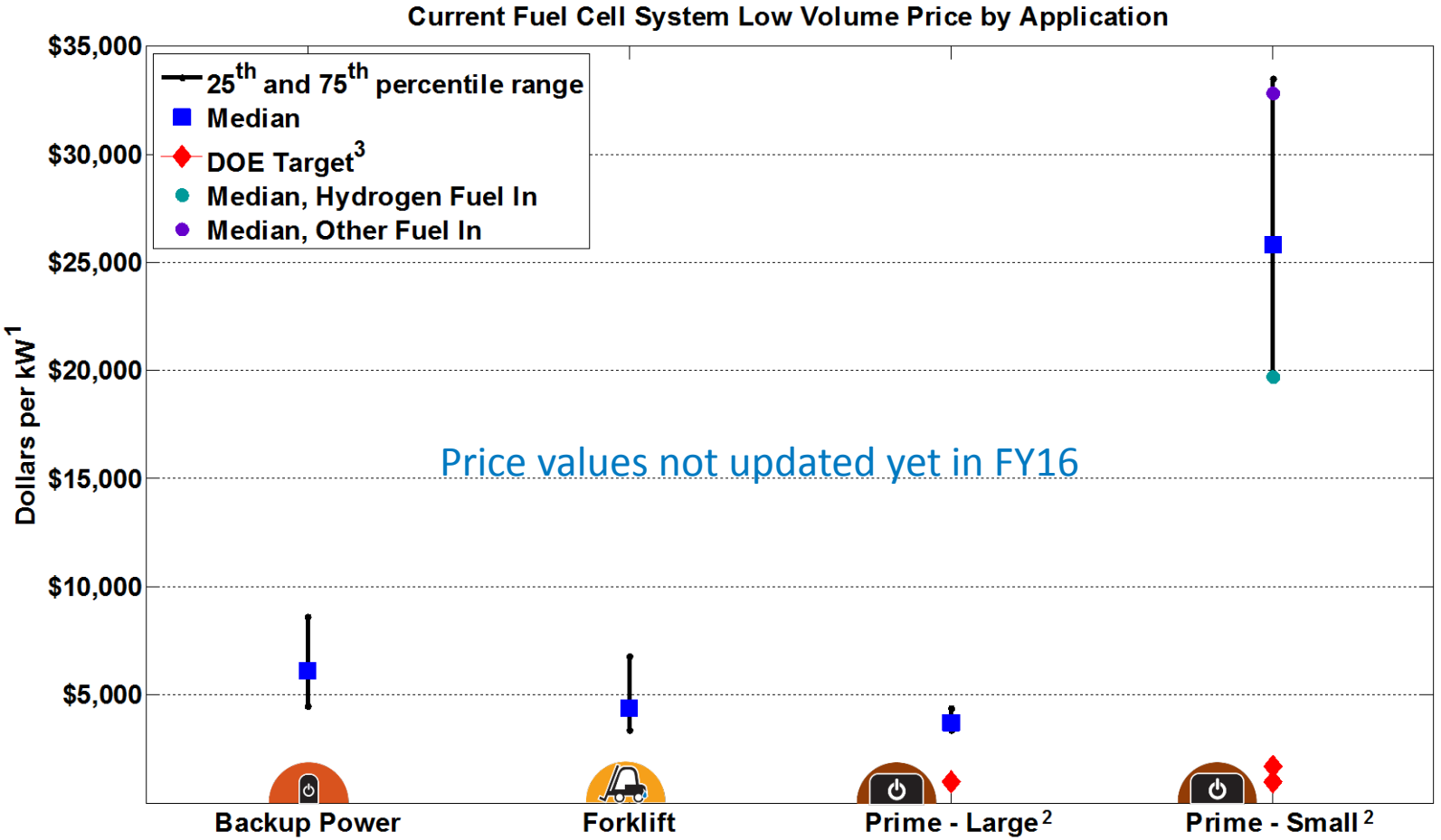
System	ProductName1	ProductName2	ProductName32	ProductName4	ProductName5	ProductName6
Current Price (US $)						
Availability						
Market						
Application						
Fuel Cell Type						
Fuel						
Comments						
Power Rating (kW)						
Other features						
# systems sold to date						
2010 Price (US $)						
2012 Price (US $)						
2014 Price (US $)						
Current system cost (US $)						
Current fuel cell stack cost (US $)						
System efficiency						
Cell count						
Active area						
Turndown capability						
Spec sheet link or Product brochure PDF attached						

	Availability	Application	Fuel Cell Type	Fuel	Other features	Markets
	Available	Stationary Prime	DMFC	Hydrogen	CHP	Europe
	Future product	Stationary Residential	PEMFC	Methanol	CHHP	Japan
	No longer available	Stationary Backup	SOFC	Reformate	Other (Please specify)	United States
	Other (Please specify)	Forklift	MCFC	Other (please specify)		All
		Automotive	PAFC	Natural Gas		Other (please specify)
		Bus	AEM	Propane		
		Portable	Other (please specify)			
		Auxiliary				
		Other (Please specify)				

Cost/Price Template

Record Source: http://www.hydrogen.energy.gov/pdfs/14014_fuel_cell_system_cost_2014.pdf

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.

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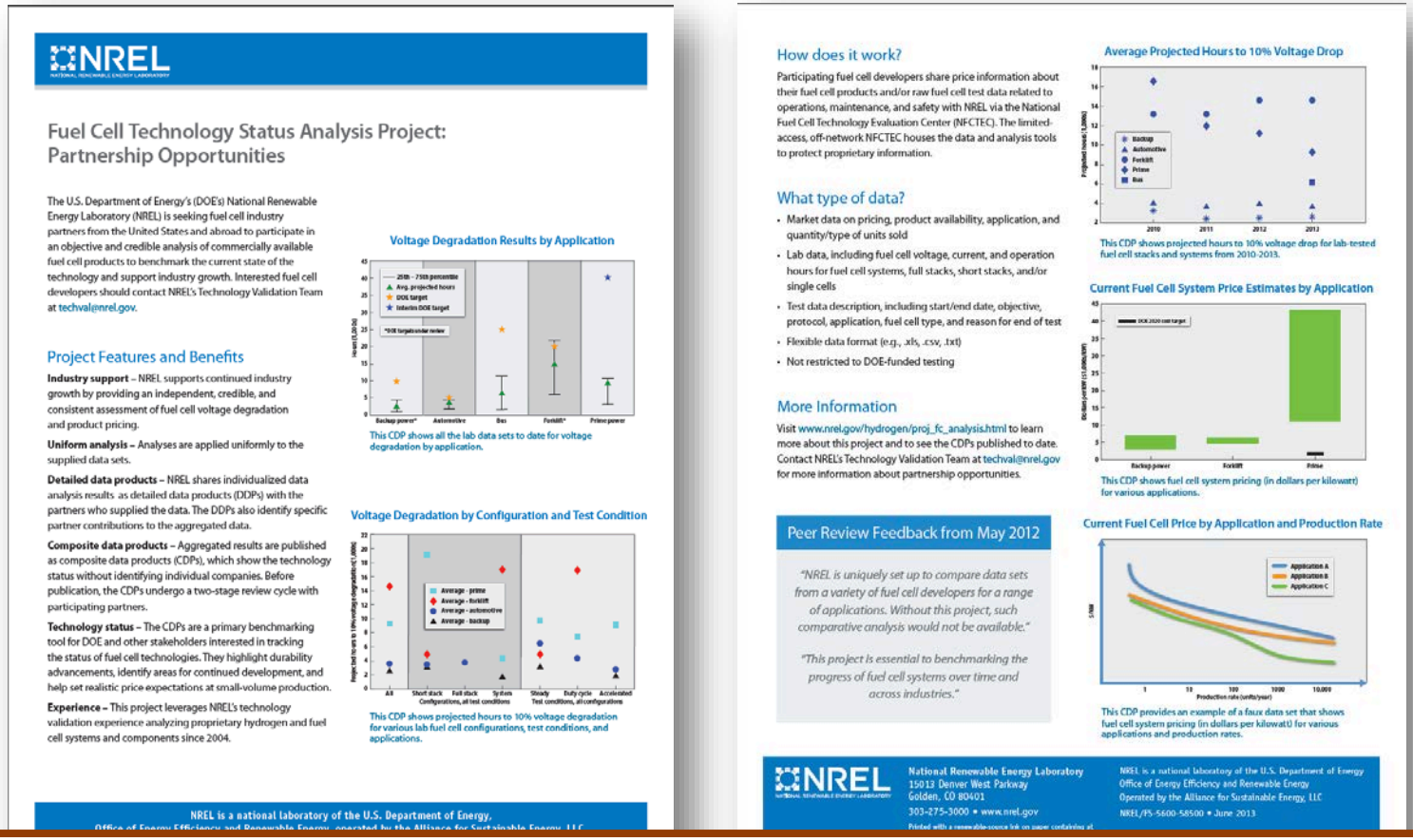
Pamphlet with Participation Details and Benefits



NREL

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.

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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.

Electrolyzer MetaData

MetaData	Input	Notes
Data Set ID		
Expected application		
Electrolysis type		
Output pressure (kPa)		
Power consumption (kW)		specify consumption based on production rate
Water consumption (L/day)		
Operating temperature ©		
Net production rate		
Specification of input water		
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)		
Current (or currenty density) points for studying degradation		Minimum is one high operation current point
Cell Count		
Active Area		

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Publications and Presentations

Publications

The following publications provide more information about NREL's fuel cell technology status analysis efforts.

- Fuel Cell Technology Status Analysis Project: Partnership Opportunities. Fact sheet describing opportunities for industry to participate in NREL's fuel cell technology performance, durability, and price/cost analysis. (September 2015)
- Fuel Cell Technology Status—Degradation: 2015 Annual Merit Review. Jennifer Kurtz, Huyen Dinh, Chris Ainscough, and Genevieve Saur. Presented at the 2015 DOE Annual Merit Review meeting. (June 2015)
- State-of-the-Art Fuel Cell Voltage Durability Status: 2015 Composite Data Products. Jennifer Kurtz, Huyen Dinh, Chris Ainscough, and Genevieve Saur. (May 2015)

All CDPs available online at http://www.nrel.gov/hydrogen/proj_fc_analysis.html

Fuel Cell Technology Status Analysis

NREL's analysis of fuel cell technology provides objective and credible information about new fuel cell technologies with a focus on performance, durability, and price. As demand for fuel cells grows, U.S. manufacturers are developing these technologies for a variety of applications. NREL helps the development community understand the current status of fuel cell technologies, identify areas for improvement, and set realistic price expectations for small-volume production.

Get Involved
Fuel cell developers interested in collaborating with NREL on fuel cell technology status analysis should send an email to NREL's Technology Validation Team at techval@nrel.gov.

Overview | Composite Data Products | Publications | Learn More | Contacts

Composite Data Products

By aggregating data from numerous developers, NREL creates composite data products (CDPs) that provide relevant data results on the technology status without revealing proprietary data or specific companies. The following CDPs focus on fuel cell usage and operation behavior:

- Lab Data Hours Accumulated and Projected Hours to 10% Stack Voltage Degradation
  CDP LAB 01, 5/11/2015
- Durability Lab Data Projection Sensitivity to Voltage Degradation Levels
  CDP LAB 02, 5/11/2015
- Field and Lab Durability Projection Comparison for Automotive Category
  CDP LAB 03, 5/11/2015
- Cumulative Operation Hours by Application and Number of Data Sets
  CDP LAB 04, 5/11/2015