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Hydrogen Fuel Cell Performance in the Key Early Markets of Material Handling Equipment and Backup Power

2013 Fuel Cell Seminar and Energy Exposition

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Columbus, Ohio

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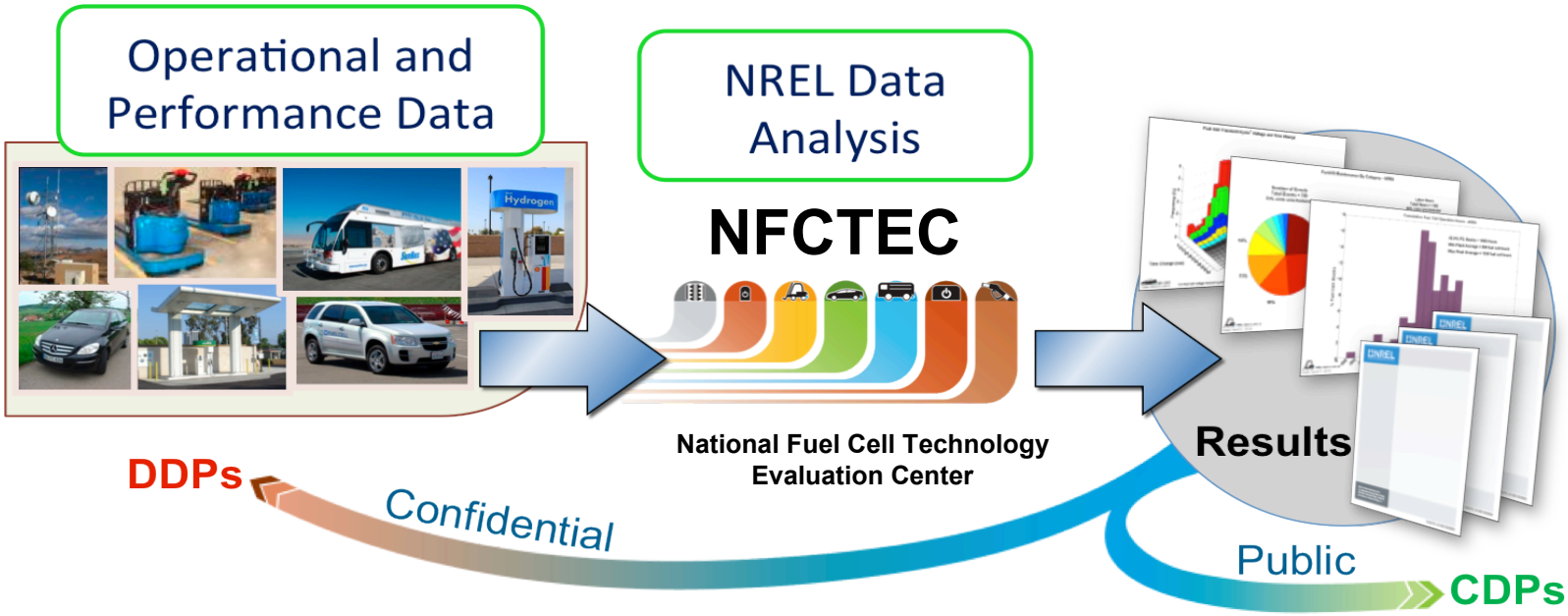
NFCTEC Analysis Approach

Analysis and reporting of real-world operation data



Detailed Data Products (DDPs)

- Individual data analyses, shared only with partner supplying data
- Identify individual contribution to CDPs

Composite Data Products (CDPs)

- Aggregated data across multiple systems, sites, and teams
- Publicly available analyses, published without revealing proprietary data

www.nrel.gov/hydrogen/proj_tech_validation.html

Objectives

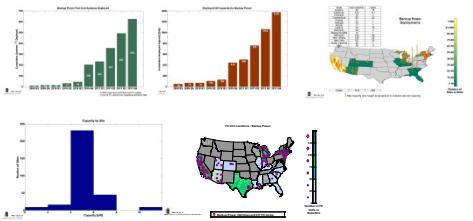
Assess the technology status in real world operations, establish performance baselines, report on fuel cell and hydrogen technology, and support market growth by evaluating performance relevant to the markets' value proposition

- **Assess technology**
  - Perform independent technology assessment in real world operation conditions
  - Focus on fuel cell system and hydrogen infrastructure: performance, operation, and safety
  - Leverage data processing and analysis capabilities developed under the fuel cell vehicle Learning Demonstration project
  - Evaluate material handling equipment (MHE) and backup power
  - Analysis includes up to 1,000 fuel cell systems deployed with American Recovery and Reinvestment Act (ARRA) funds
- **Support market growth**
  - Provide analyses and results relevant to the markets' value proposition
  - Report on technology status to fuel cell and hydrogen communities and other key stakeholders such as end users

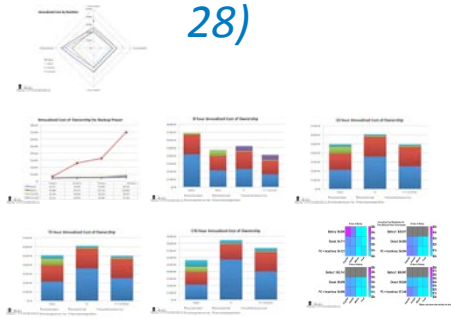
28 Backup Power CDPs—Count and Category

BACKUP POWER

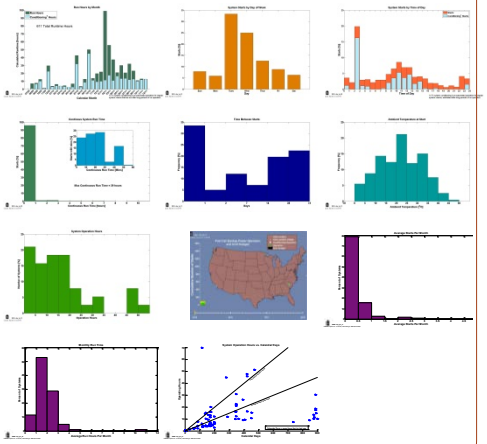
Deployment
(1, 2, 3, 14, 19)



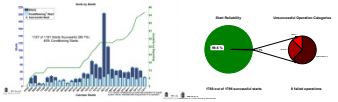
Cost of Ownership
(22, 23, 24, 25, 26, 27, 28)



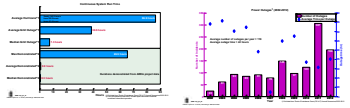
Fuel Cell Operation
(5, 7, 8, 9, 11, 12, 13, 15, 16, 17, 21)



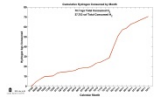
Fuel Cell Reliability
(4, 10)



U.S. Grid Outage Stats
(18, 20)



Infra. Operation
(6)



Backup Power Operation Summary
2009 Q1–2013 Q2

BACKUP POWER

1.94
Installed capacity in MW

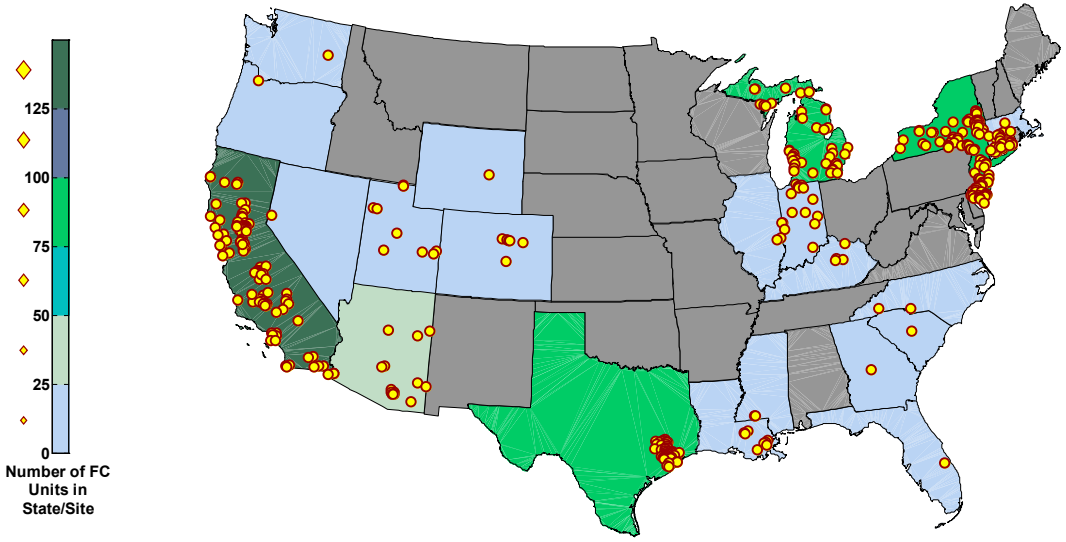
Systems are operating reliably in 23 states. Reasons for unsuccessful starts include an e-stop signal, no fuel, and other system failures.

99.7%
Successful starts

842
Systems in operation*

4–6
Average site capacity in kW

2,579
Start attempts



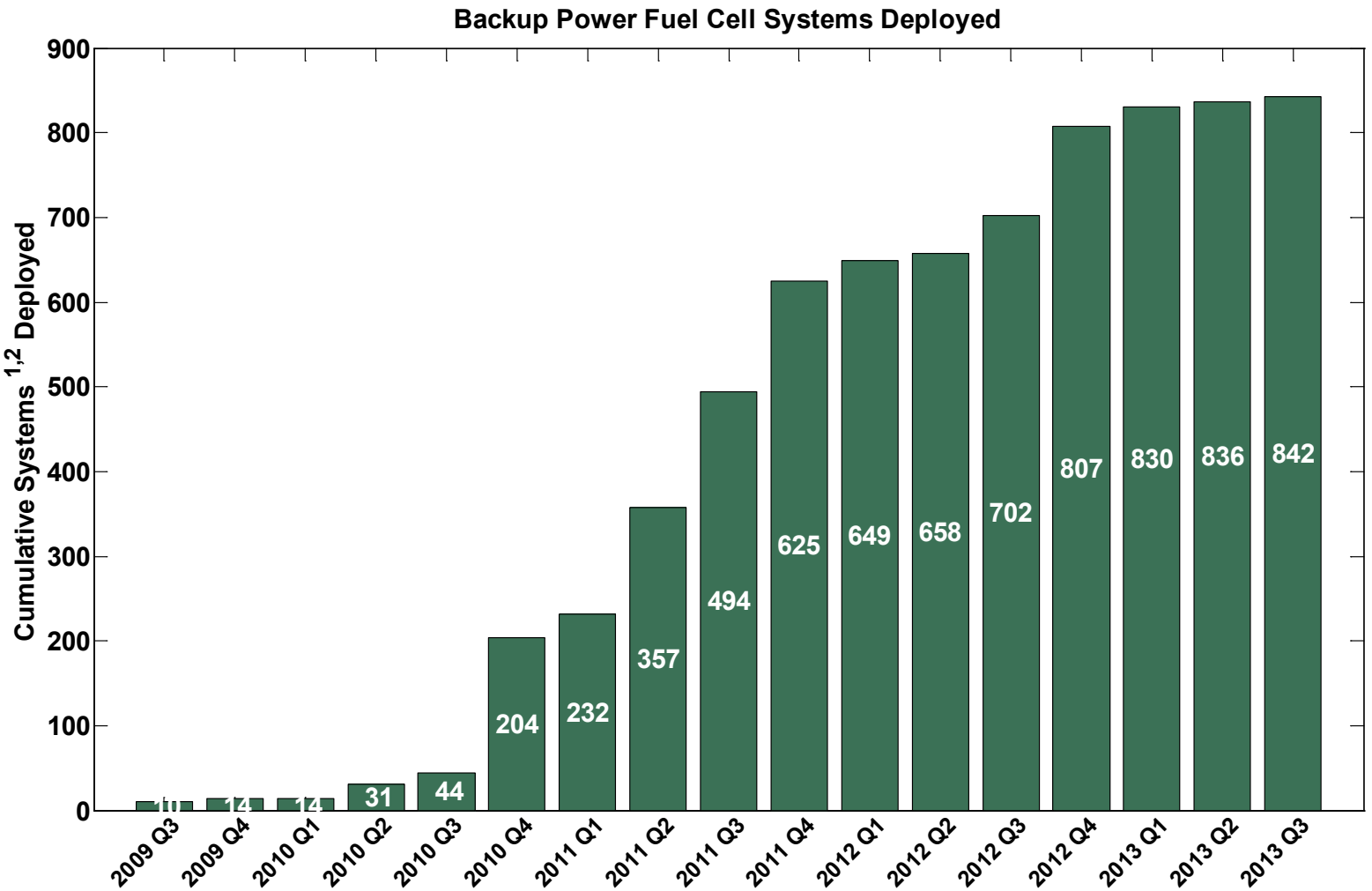
65
Continuous run hours demonstrated

1,683
Operation hours

*Not all systems have detailed data reporting to NREL

Backup Power Fuel Cell Systems Deployed

BACKUP POWER



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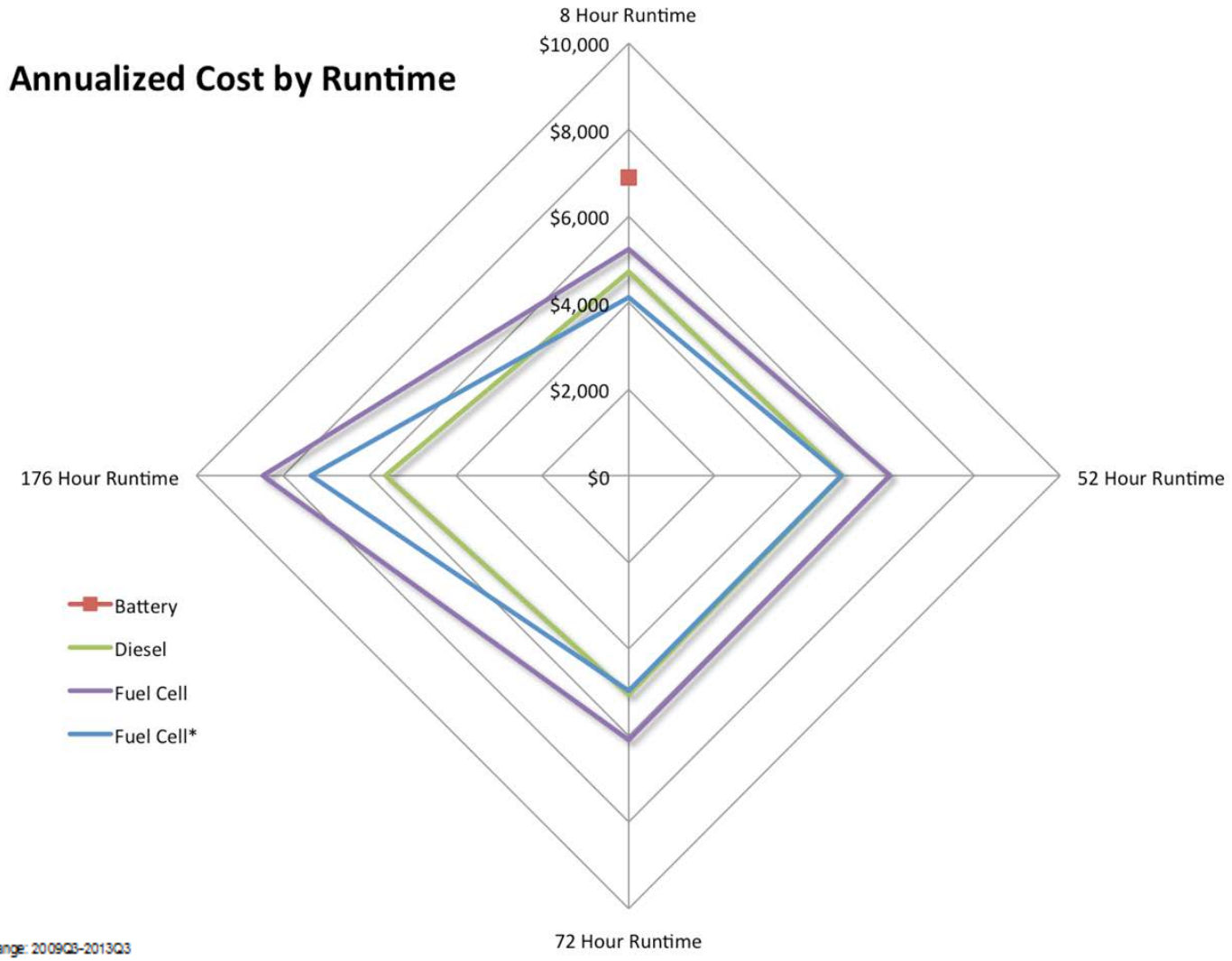
1) Sites may have more than one FC system
2) Not all FC systems are supplying operation data

Annualized Cost by Runtime

BACKUP POWER



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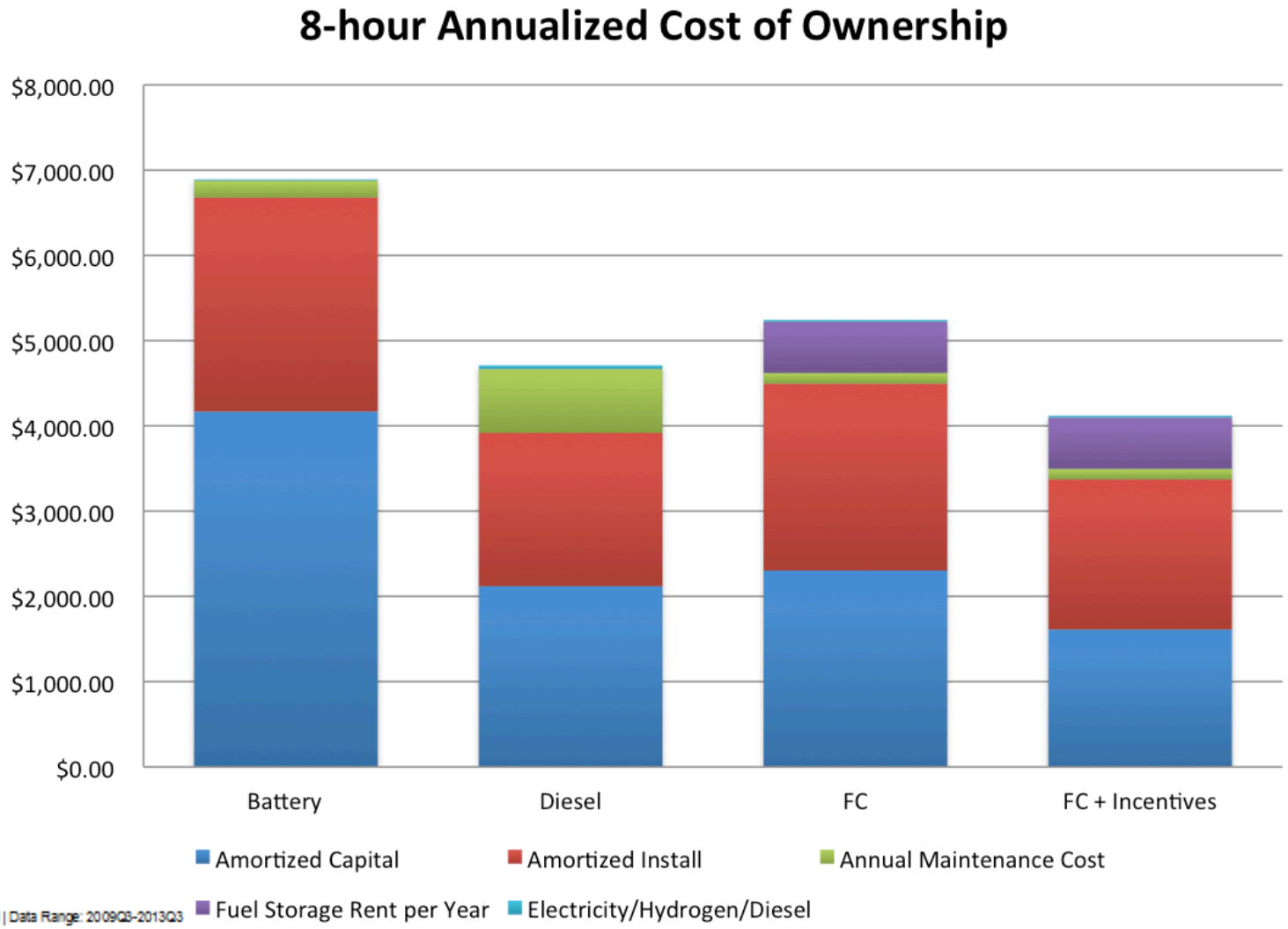
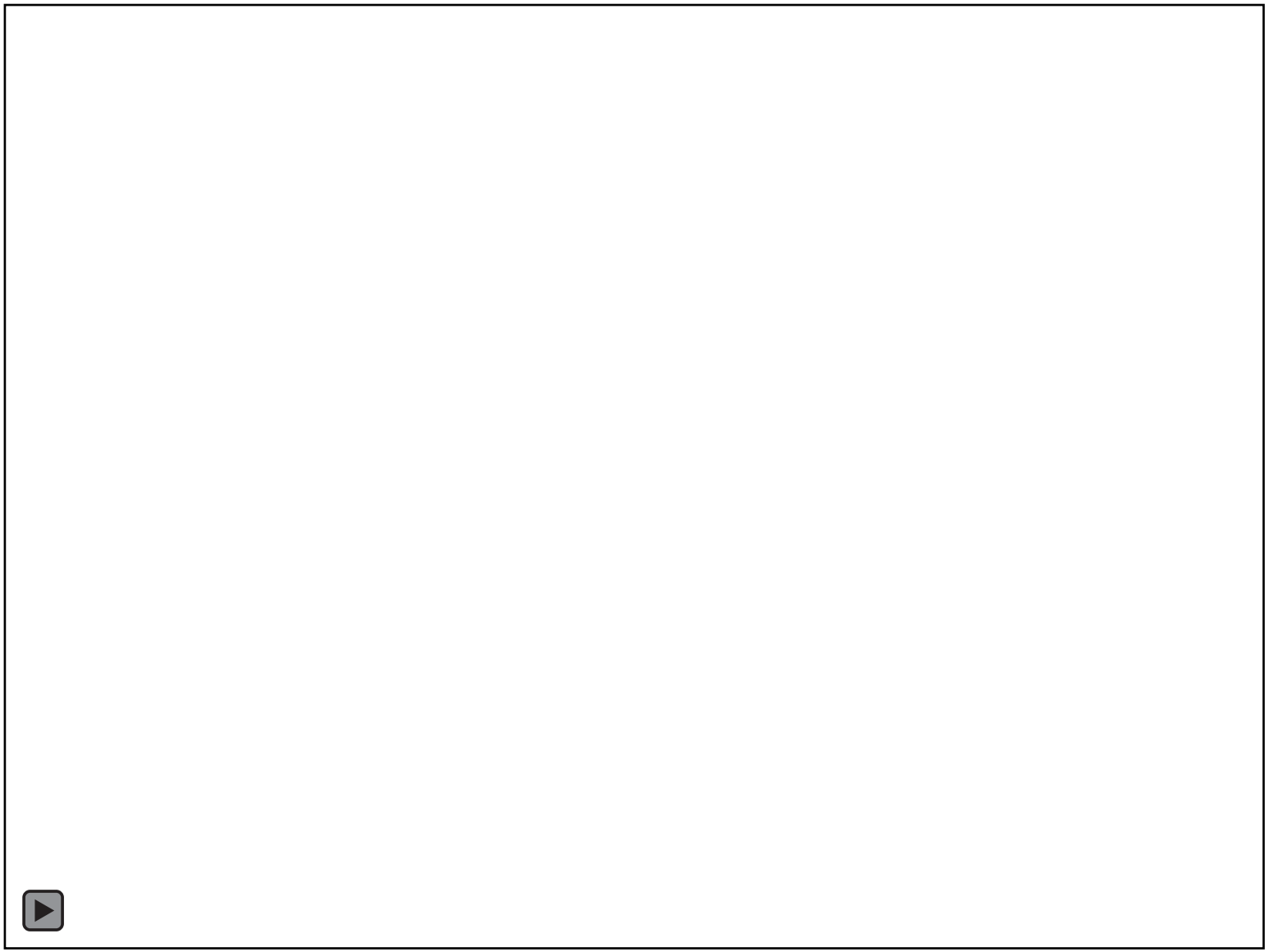
8-Hour Annualized Cost of Ownership

BACKUP POWER



Analysis of Fuel Cell Backup Power Operation with U.S. Grid Outage from 01/2010 through 08/2013

BACKUP POWER



74 MHE CDPs—Count and Category

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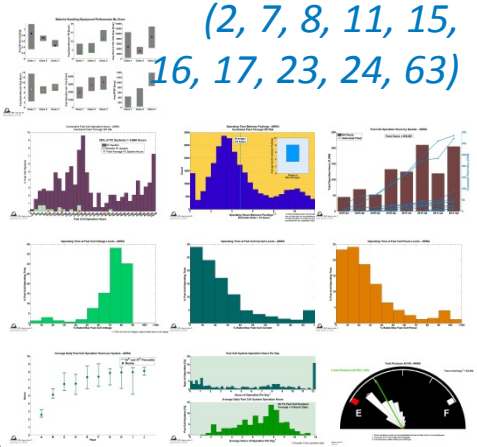
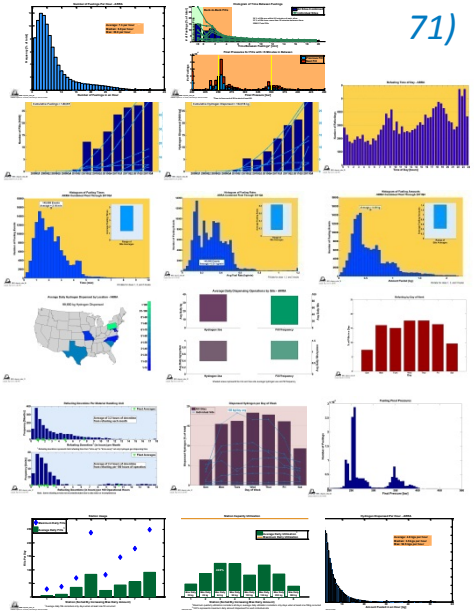
Deployment & Site Overview *(1, 40)*

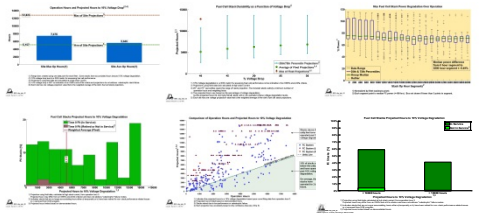
Fuel Cell Operation *(2, 7, 8, 11, 15, 16, 17, 23, 24, 63)*



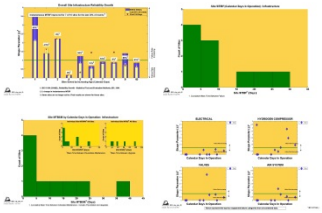
Infra. Operation *(3, 4, 5, 6, 9, 10, 21, 22, 35, 37, 42, 62, 65, 68, 69, 70, 71)*



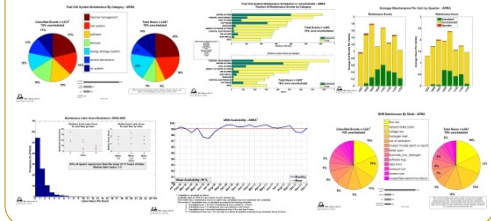
Fuel Cell Durability *(32, 33, 34, 38, 39, 73)*



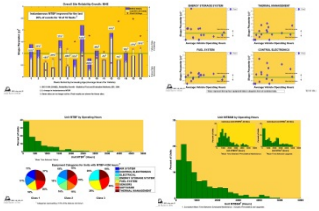
Infra. Reliability *(45, 48, 49, 50)*



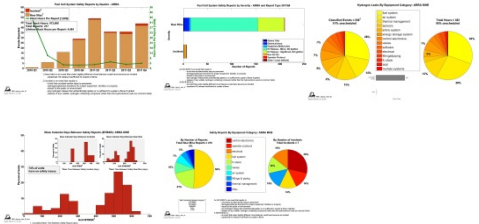
FC Maintenance *(12, 13, 14, 43, 54, 61)*



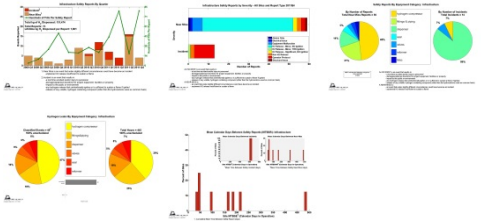
Fuel Cell Reliability *(28, 29, 30, 31)*



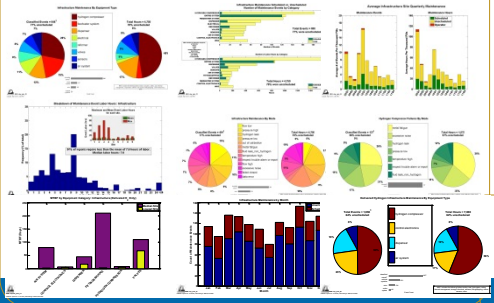
Fuel Cell Safety *(26, 27, 53, 56, 57)*



Infra. Safety *(25, 41, 46, 51, 55)*



Infra. Maintenance *(18, 19, 20, 44, 47, 52, 66, 67, 72,76,77)*



Cost of Ownership *(58, 59, 60,64)*

MHE Operation Summary
2009 Q4–2013 Q2

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Validation of MHE is based on real-world operation data from high-use facilities

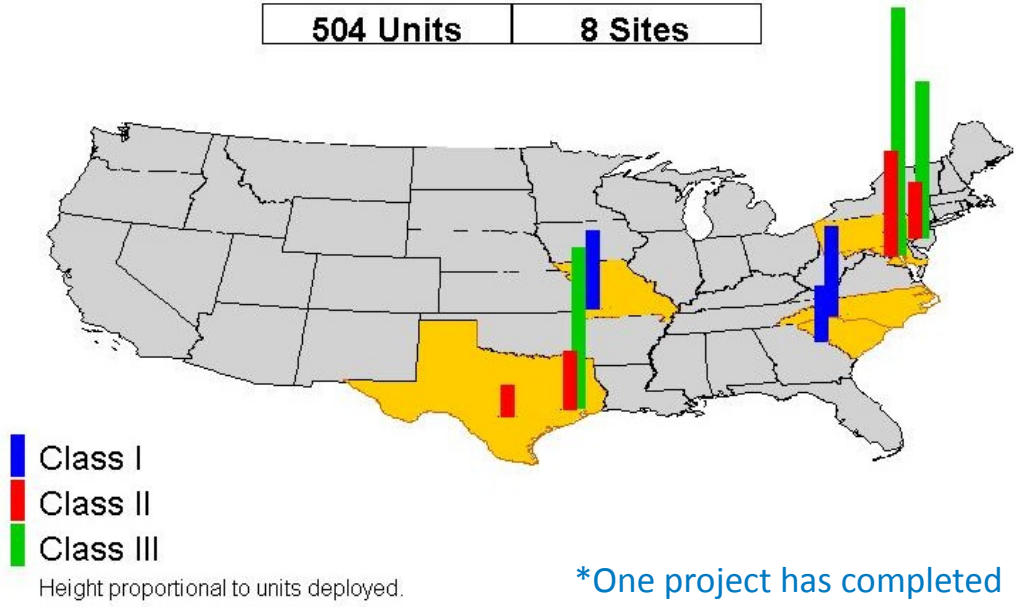
1,859,616
Operation hours

291,114
Hydrogen fills

490
Units in operation*

4.4
Average operation hours between fills

232,551
Hydrogen dispensed in kg

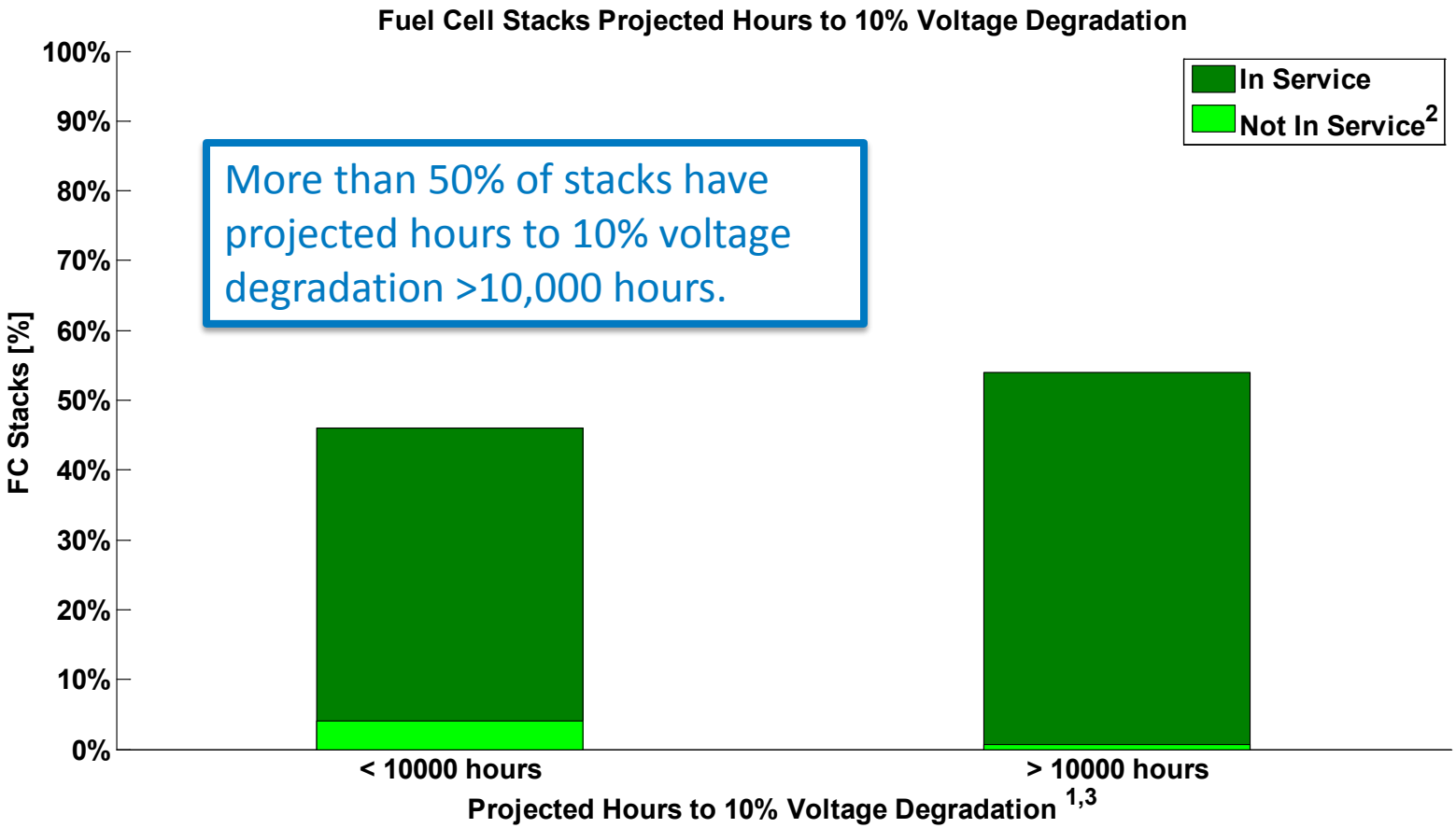


0.6
Average fill amount in kg

2.3
Average fill time in minutes

*One project has completed

Study of FC Voltage Degradation Against 10,000 Hours



1) Projection using field data, calculated at high stack current, from operation hour 0.
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.

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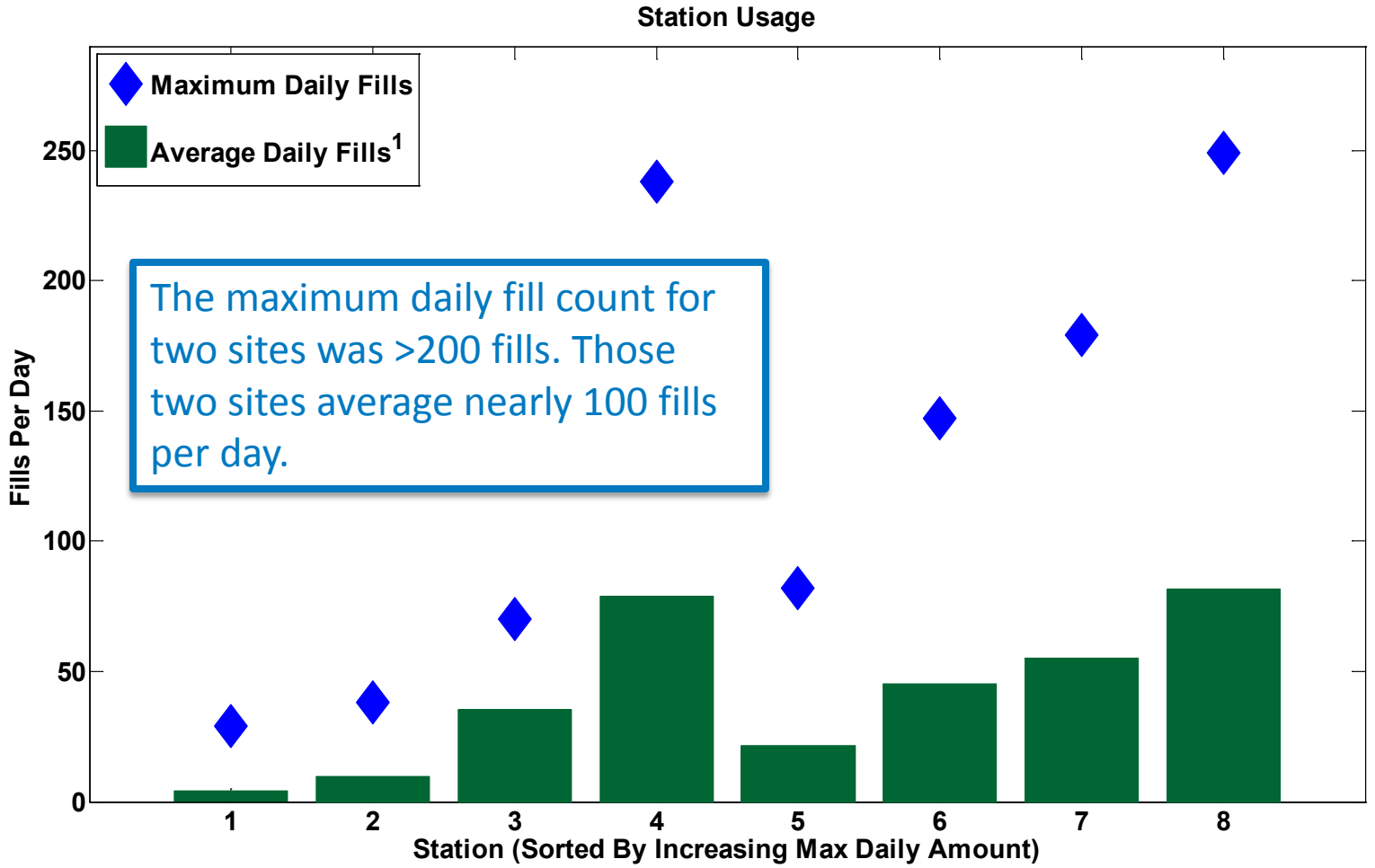
Study of Infrastructure Usage by Daily Fills



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[1]Average daily fills considers only days when at least one fill occurred

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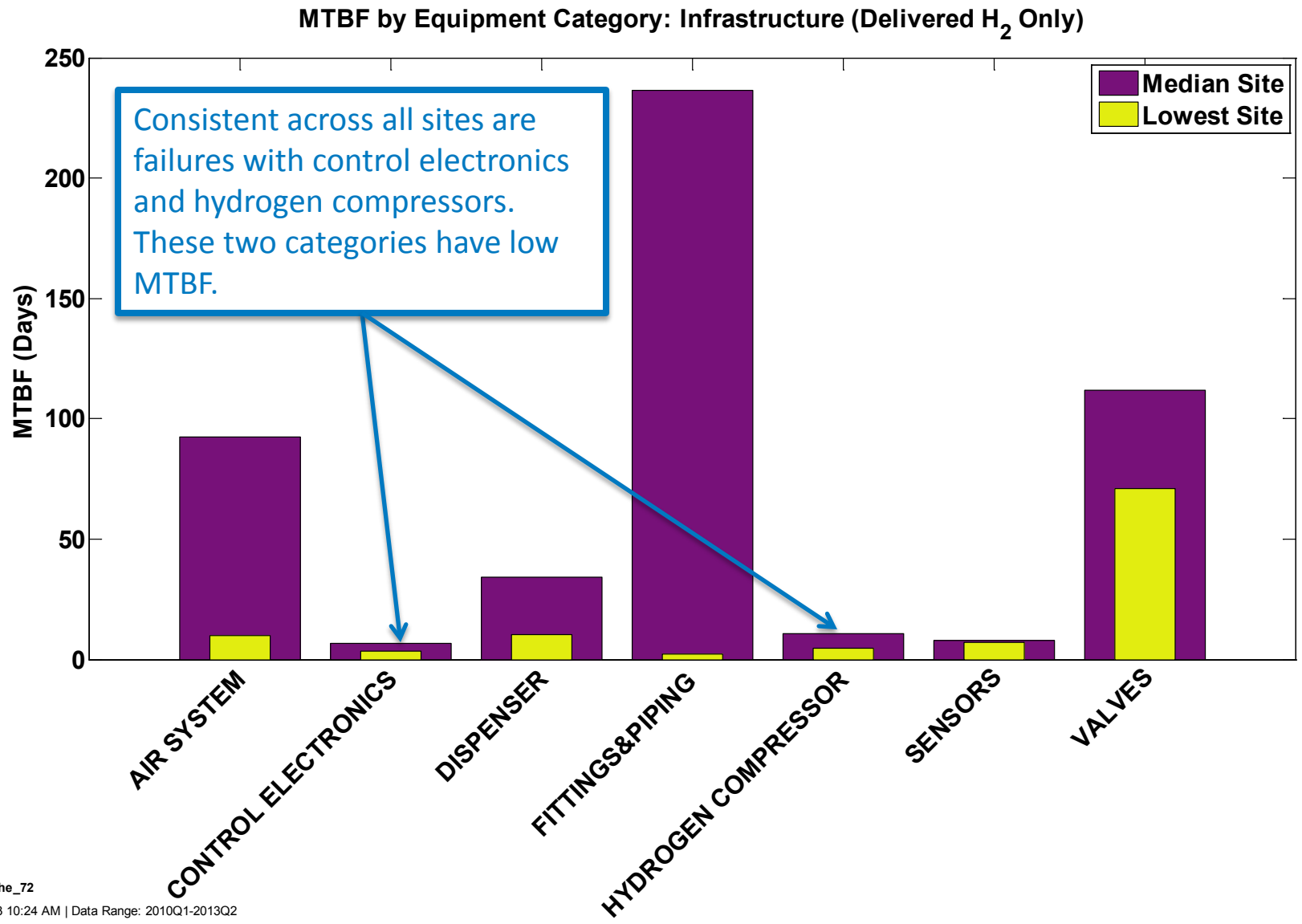
Breakdown of MTBF by Key Delivered Hydrogen Infrastructure Categories



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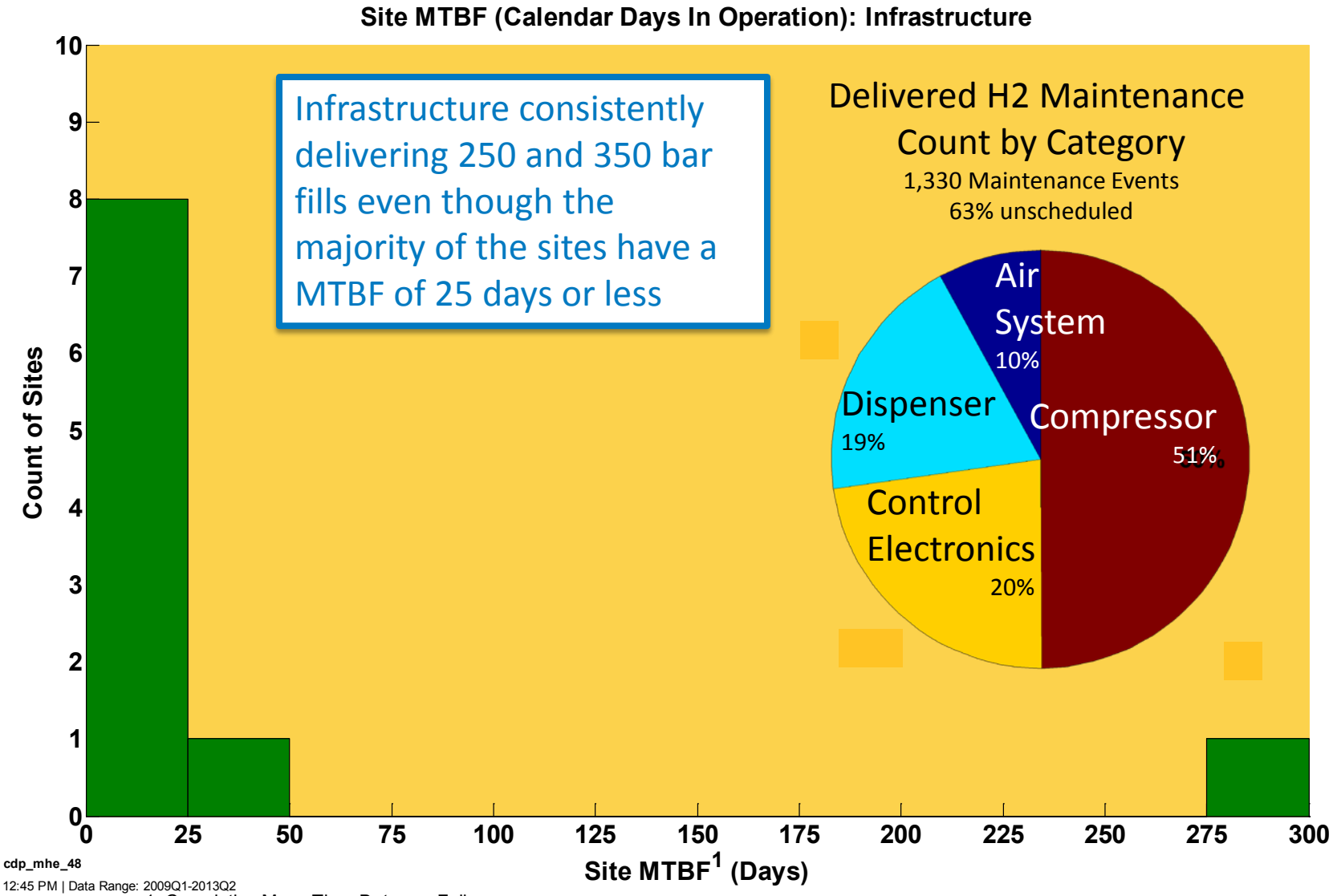
Infrastructure Reliability Analysis



NREL cdp_mhe_48

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1. Cumulative Mean Time Between Failure

Breakdown of Failure Modes for Top Four Maintenance Categories for Infrastructure

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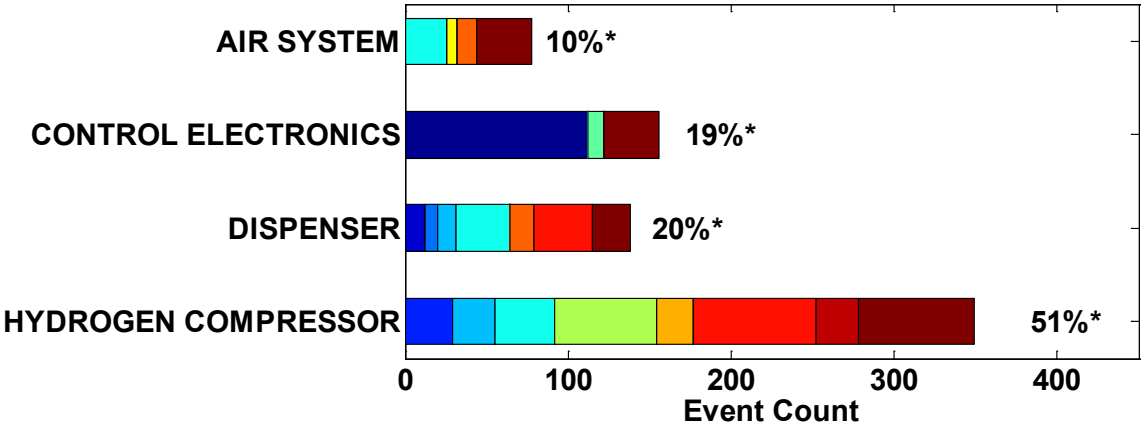
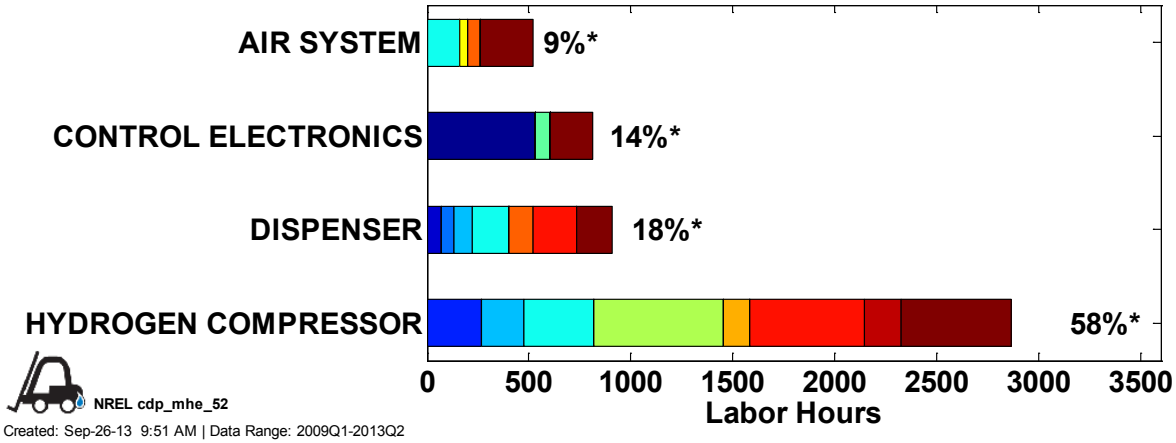
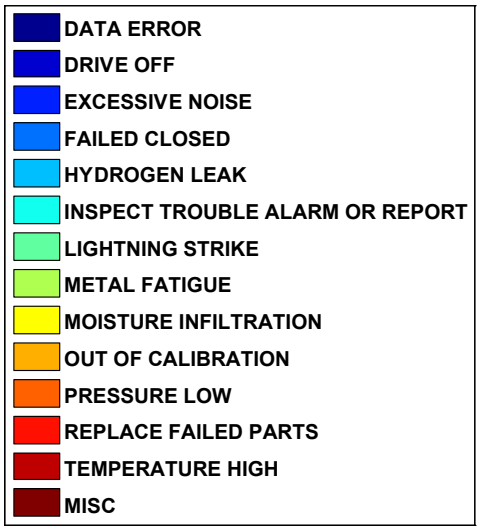
There are many different failure modes for the top four categories and these modes provide insight for RD&D needs







MISC includes the following failure modes: ambient temperature too low, broken wire, cavitation, data error, debris infiltration, electrical short, failed closed, false alarm, flow high, flow low, fluid leak non-hydrogen, fluid leak non_hydrogen, fluid leak_non_hydrogen, inspect trouble alarm or report, maintenance error, manufacturing defect, metal fatigue, moisture infiltration, network malfunction, operator protocol, other, power outage, pressure high, pressure low, replace failed parts, software bug, unspecified electronics failure, vandalism, voltage low, other

*** Percentage of total events or hours, reference CDP 66.**

NREL cdp_mhe_52

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Technical Summary—*What We've Learned*

Fuel Cell Backup Power

- Operating reliability in 23 states with 99.7% successful starts.
- Maximum continuous run time of 65 hours due to an unplanned grid outage.

Fuel Cell Material Handling Equipment

- Operating with an average availability of ~98% at eight end-user facilities.
- Most systems operate at least 6 hours a day.
- Cost of ownership comparison between fuel cell and battery MHE indicate significant cost savings for refueling labor and infrastructure space but much greater cost for hydrogen infrastructure and fuel.

Aggregated data showcase performance over the last two years in MHE and backup power.

Performance results address a need for published results on the technology status.

Data analyses develop as systems operate and based on the key performance areas in the markets.

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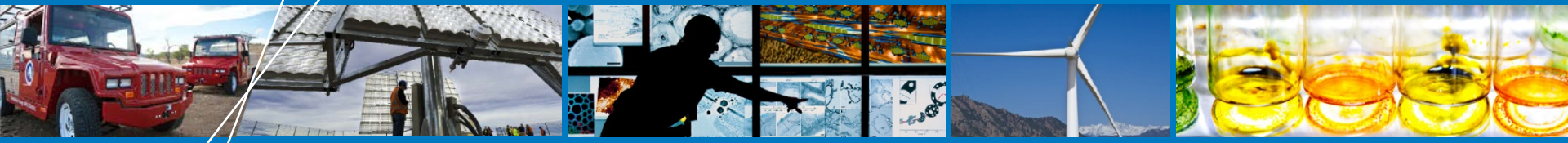

Backup Slides

Published MHE Cost of Ownership Report

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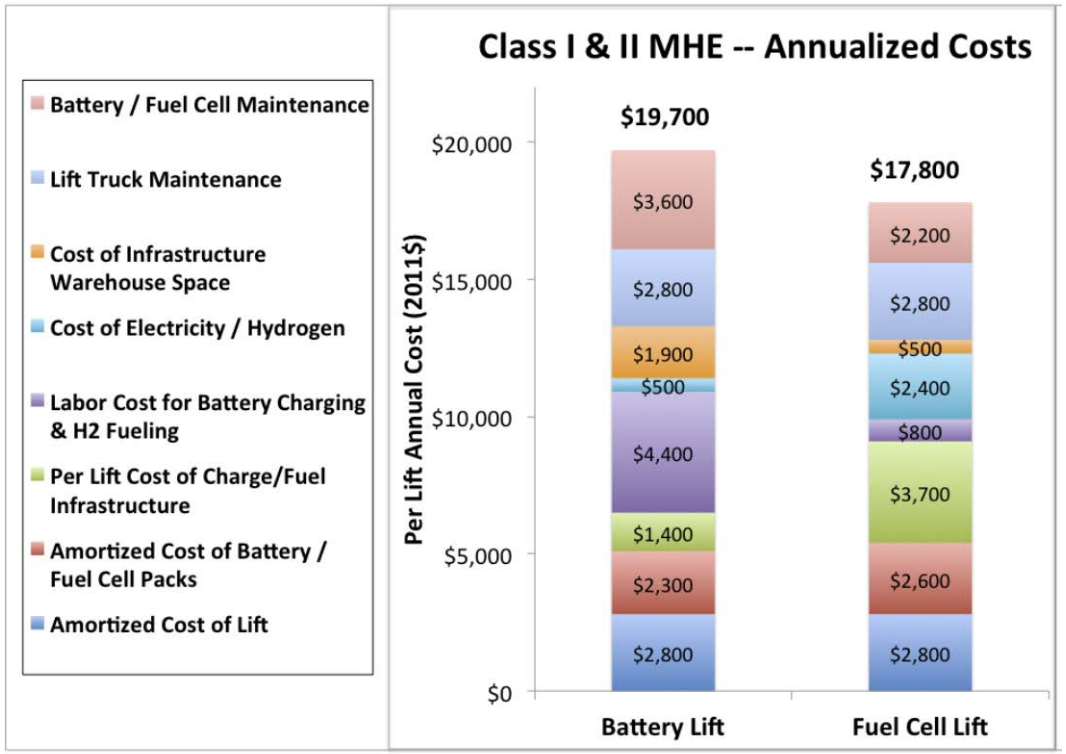
Cost advantage per unit is ~$2,000/year for the average high-use facility with Class I and II fuel cell lift trucks analyzed by NREL



Key Findings

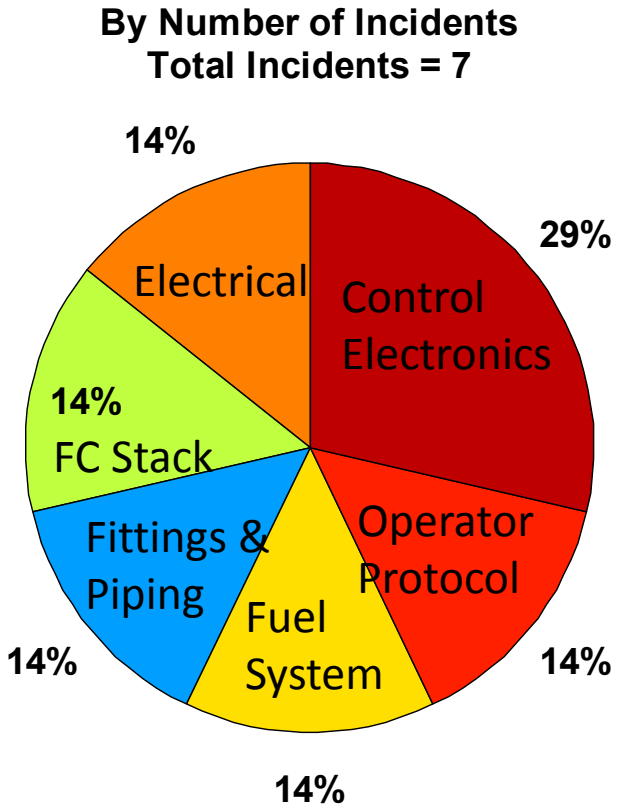
- Cost advantages dependent on deployment size and use (i.e., multi-shift operation per day)
- H_2 fuel cell cost advantages in maintenance, warehouse infrastructure space, and refueling labor cost
- H_2 fuel cell cost disadvantages in infrastructure and fuel cell cost and hydrogen cost

Report Sections

- Inputs, assumptions, and results for Class I/II and Class III
- Sensitivity study
- Intensive deployment scenario

MHE and Infrastructure Safety Report Analyses

Majority of MHE safety reports (217) are minor hydrogen leaks
(4,480 stack hours per report)



Majority of infrastructure safety reports (82) are hydrogen leaks primarily from the hydrogen compressor and plumbing
(3,587 kg dispensed per report)