NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Performance & Reliability of Fuel Cell Systems in the Field

Fuel Cell End Users' Forum

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February 4th, 2013

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

Outline

- Combined Results
- Light Duty Vehicle results from the U.S. DOE Learning Demonstration Project: 2004 – 2012
- American Recovery & Reinvestment Act (ARRA) fuel cell backup power & material handling and systems.

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Project Approach

Supporting Both DOE/Public as Well as Technology Developers

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

Internal analysis completed quarterly

HSDC

NREL's Hydrogen Secure Data Center

Results

DDPs

Confidential

Public

CDPs

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)

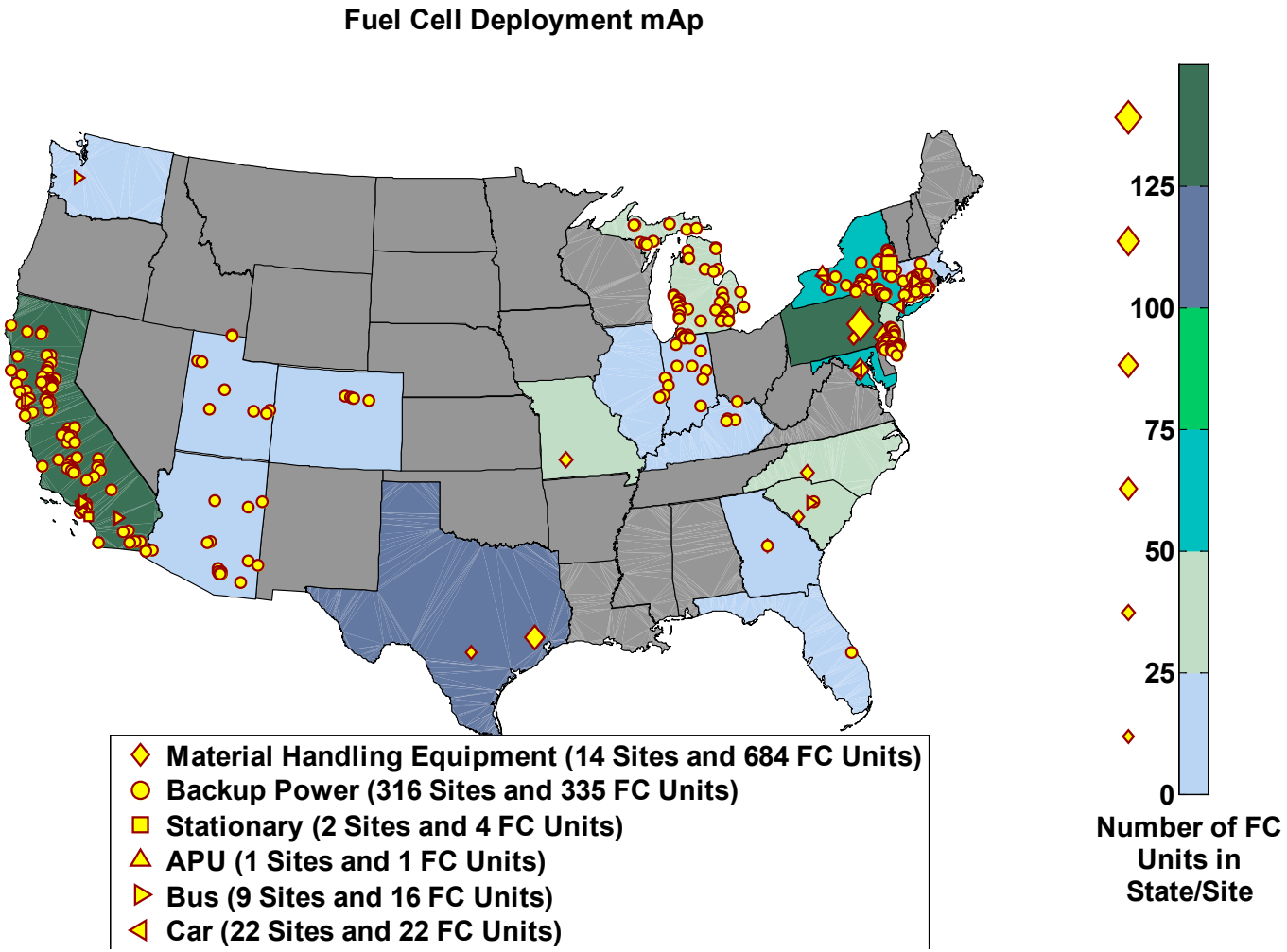
- Aggregated data across multiple systems, sites, and teams
- Publish analysis results every six months without revealing proprietary data[2]

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)

Combined Results

Deployments we track

BACKUP POWER | FORKLIFTS | BUSES | CARS



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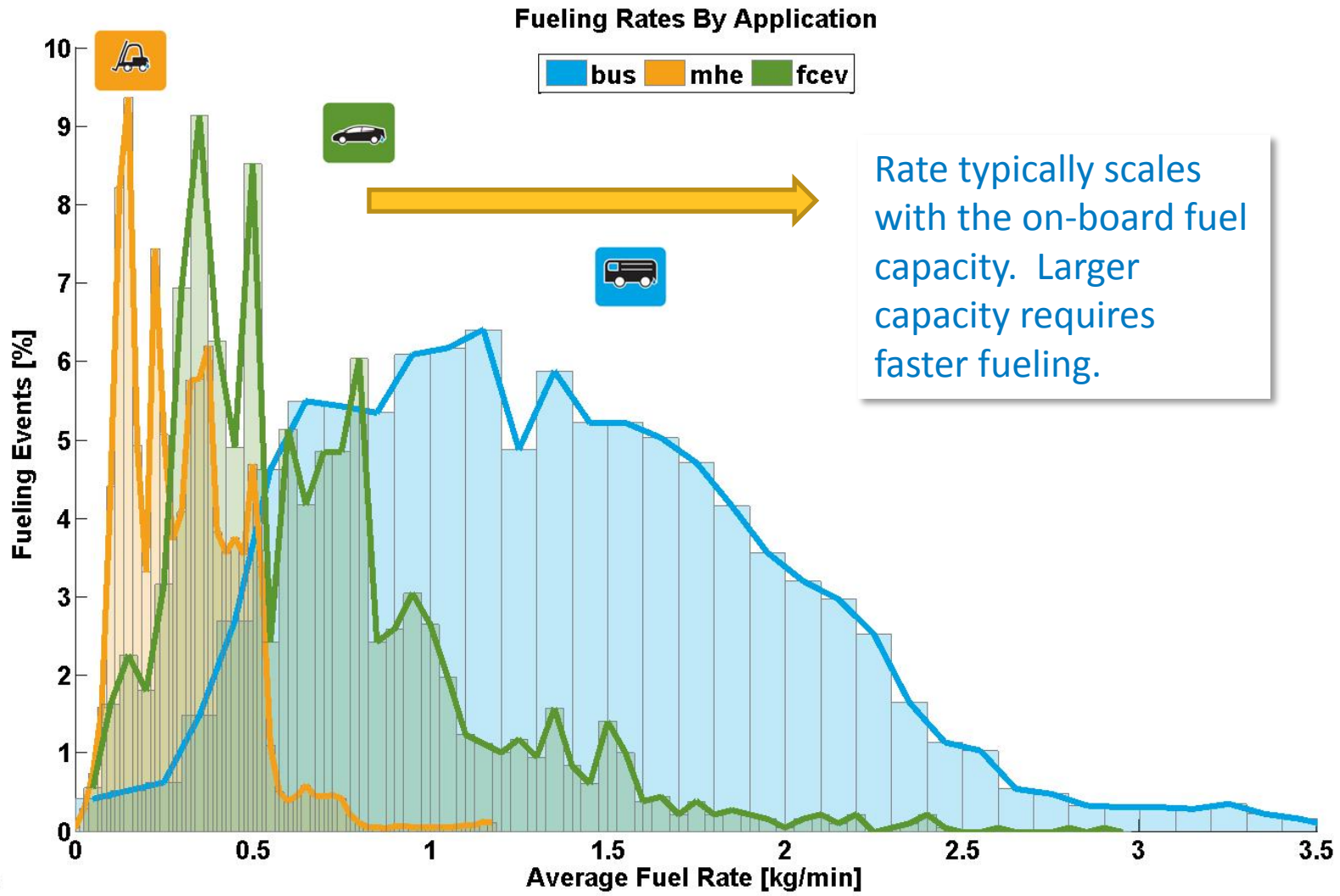
Fueling Rates



Rate typically scales with the on-board fuel capacity. Larger capacity requires faster fueling.

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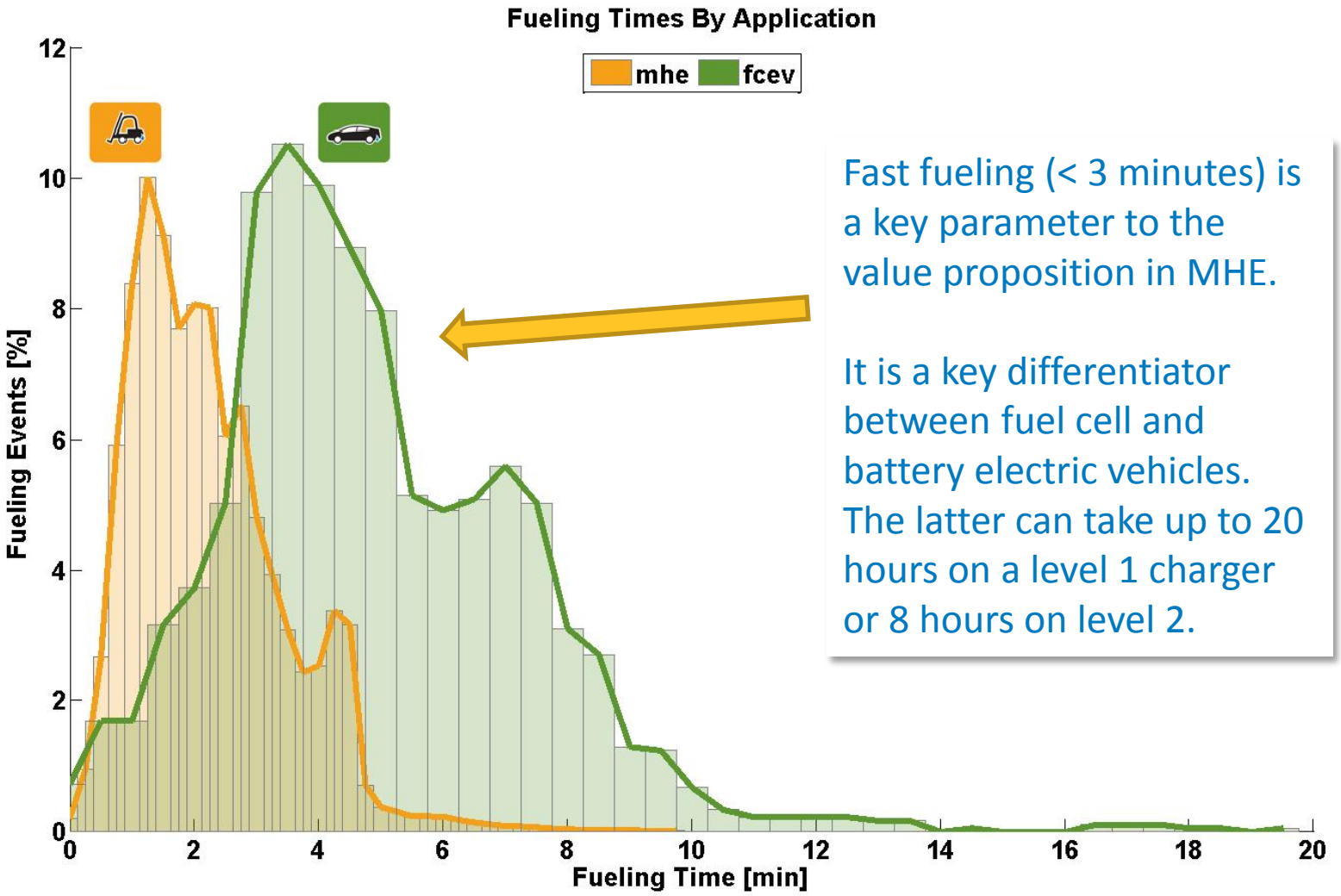
Fueling Times



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Fast fueling (< 3 minutes) is a key parameter to the value proposition in MHE.

It is a key differentiator between fuel cell and battery electric vehicles. The latter can take up to 20 hours on a level 1 charger or 8 hours on level 2.

Light Duty Vehicles

2nd Generation Vehicles Demonstrated Technology Improvements Over Gen 1

Generation 1 Vehicles

- FC not freeze-capable
- ~2003 stack technology
- Storage: liquid H2 & 350 and 700 bar
- Range: 100-200 miles
- Efficiency: 51-58% at ¼ power

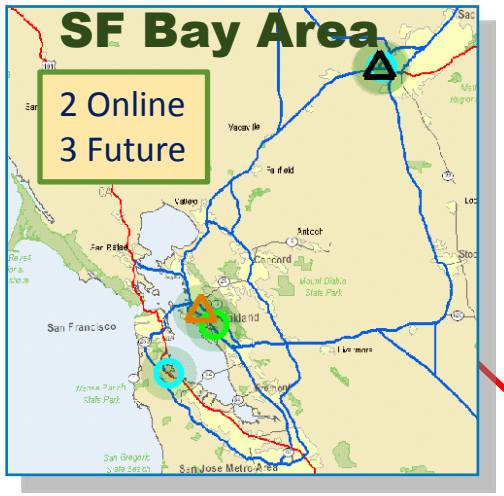
Generation 2 Vehicles

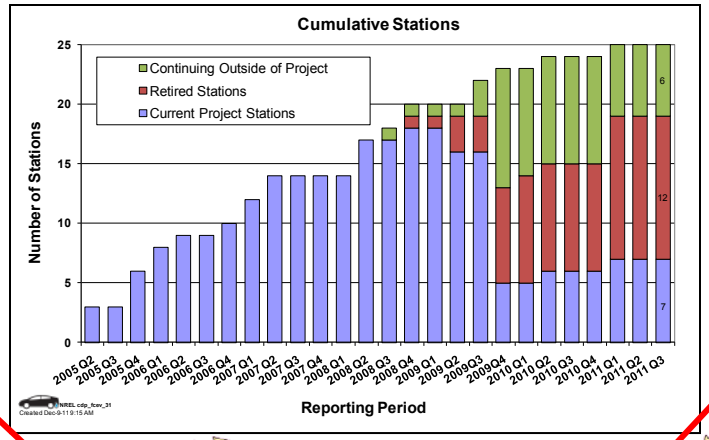
- FC freeze-capable
- ~2007-2009 stack tech.
- Storage: All 700 bar
- Range: 200-250 miles
- Efficiency: 53-59% at ¼ power
- Longer FC durability

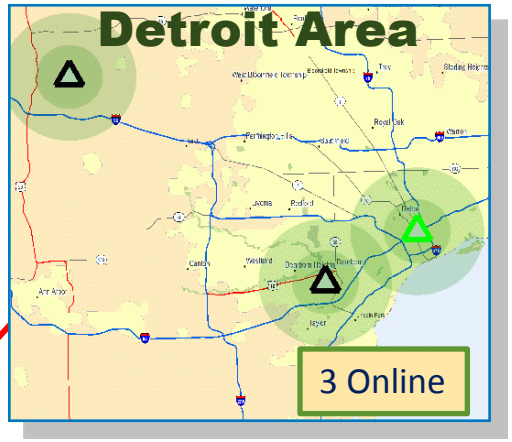
Infrastructure Status: Out of 25 Project Stations, 13 Are Still Operational* (6 outside of DOE project)

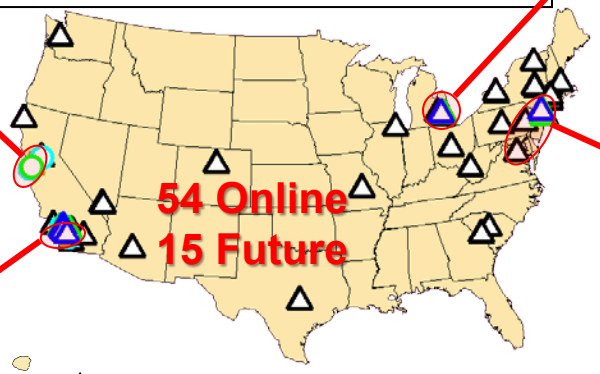
CARS

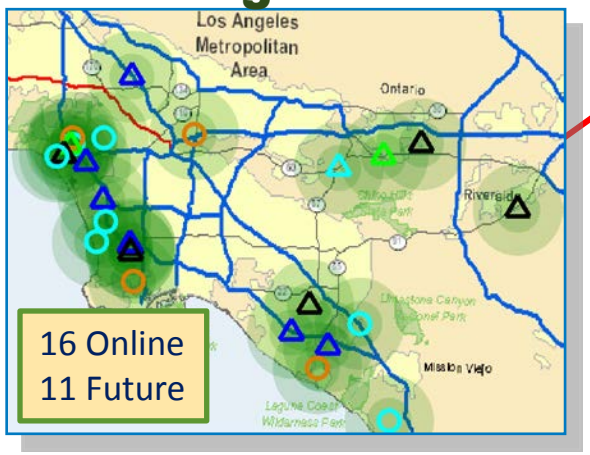
* CDP station status is as of 9/30/11

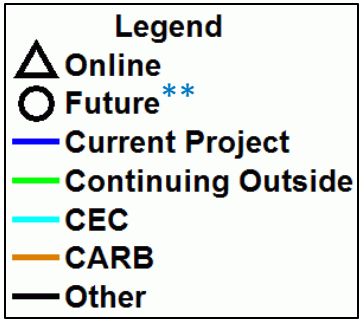








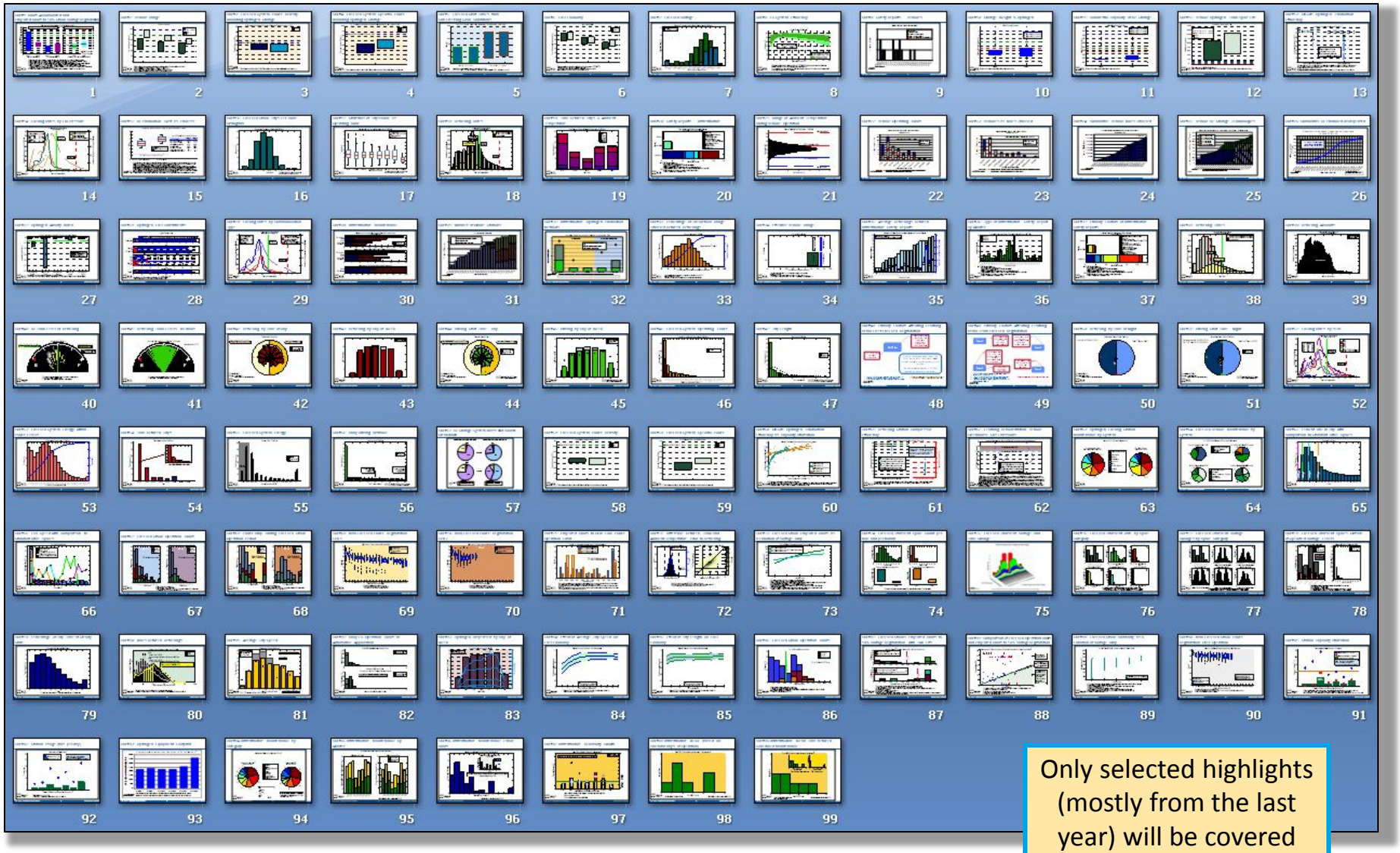




** Funded by state of CA or others, outside of this project

Total of 99 CDPs Published, Including 40 Winter 2011 CDPs

CARS



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

Project Achieved Both Technical Goals; Outside Analysis Used for Cost Evaluation

CARS

1)

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

2)

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%	--

3)

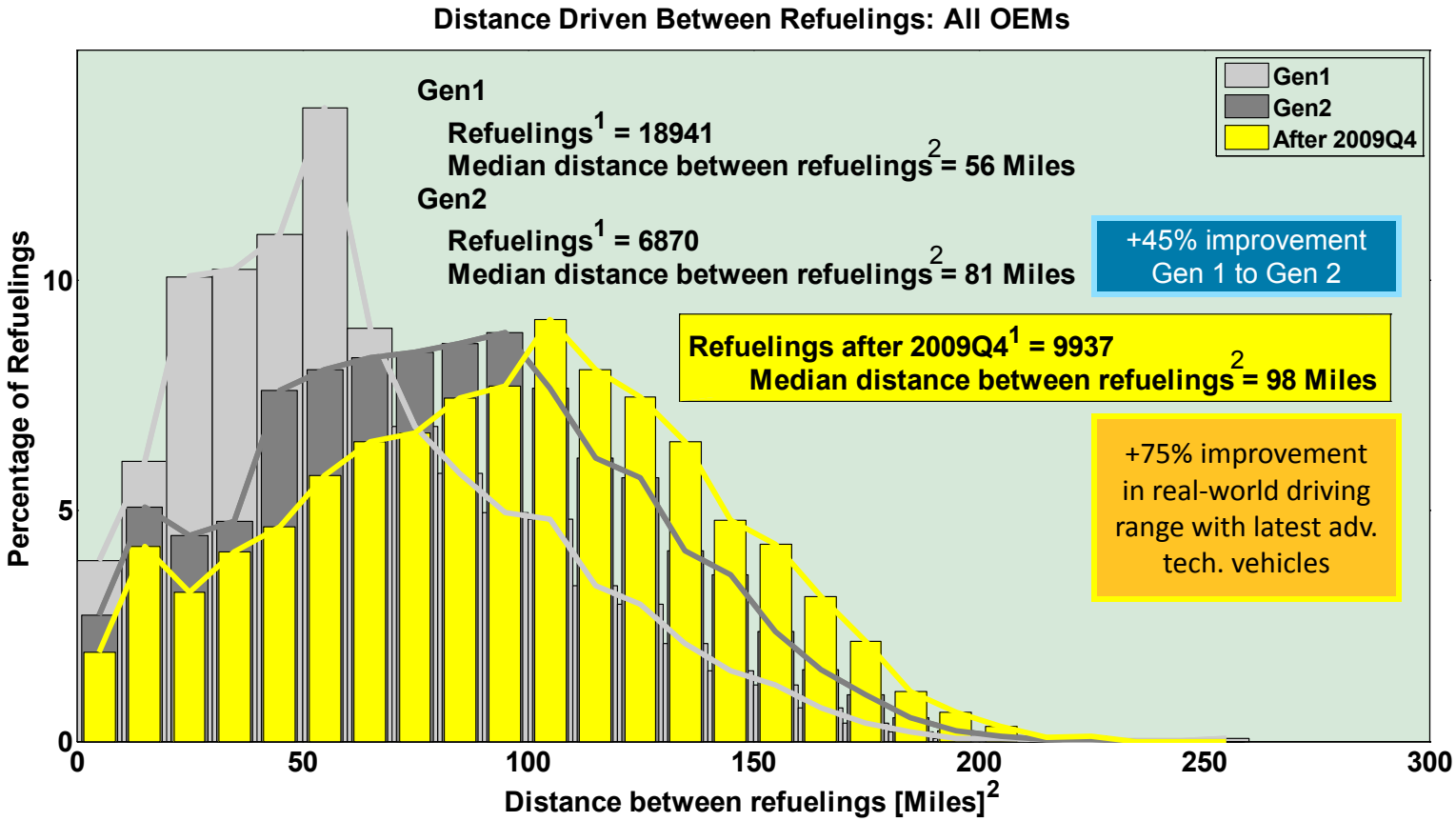
Infrastructure Performance Metrics			2009 Target	After 2009Q4
H_2 Cost at Station (early market)	On-site natural gas reformation **$7.70 – $10.30/kg**	On-site Electrolysis **$10.00 – $12.90/kg**	**$3/gge**	--
Average H_2 Fueling Rate	0.77 kg/min		1.0 kg/min	0.65 kg/min

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

RANGE: Results Show Significant Improvement in Real-World Driving Range Between 3 Sets of Vehicles

CARS



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.

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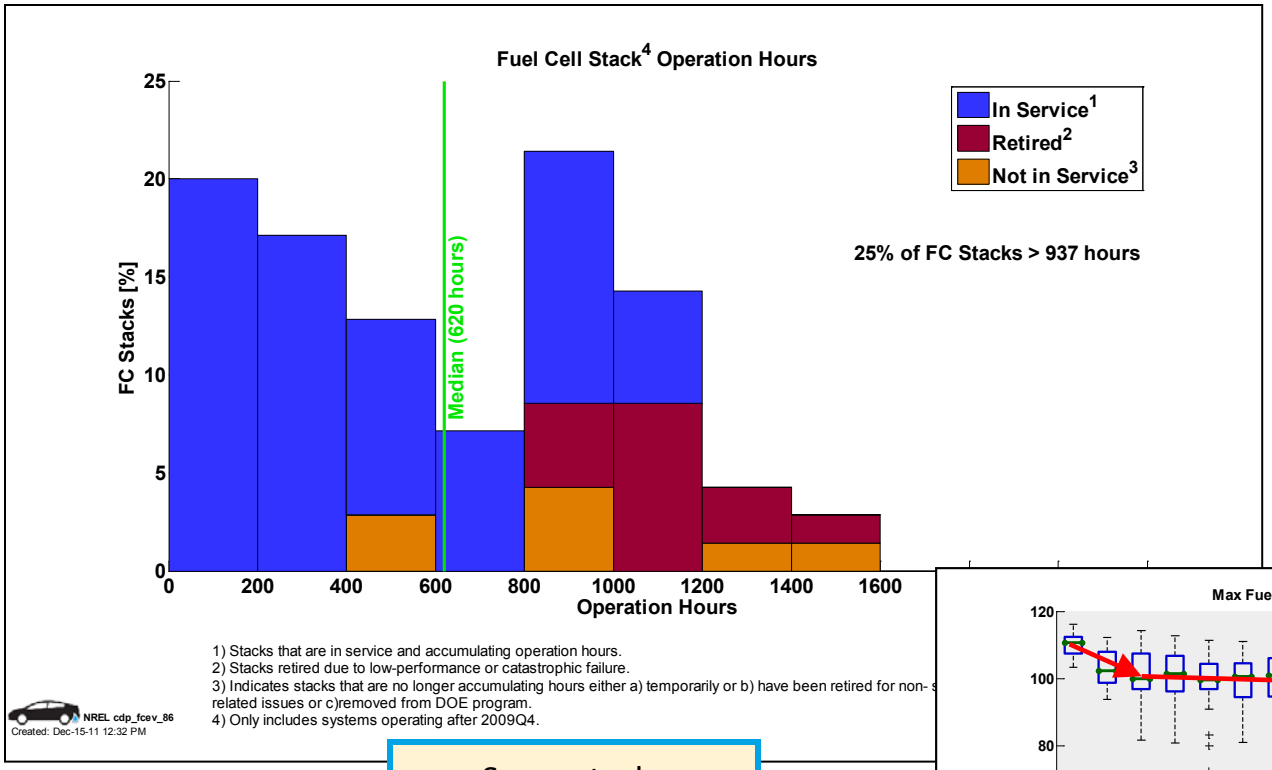
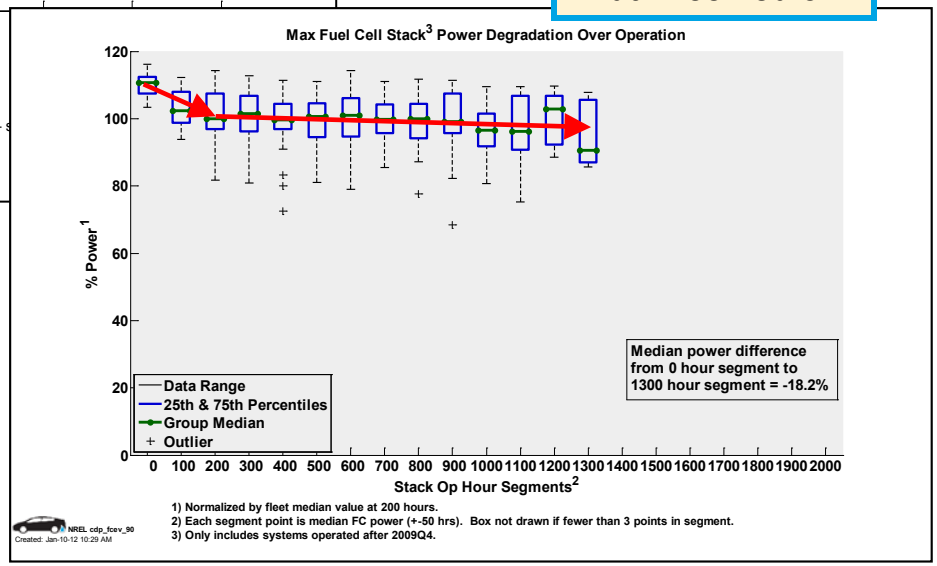
Note: Actual range possible >200 miles

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

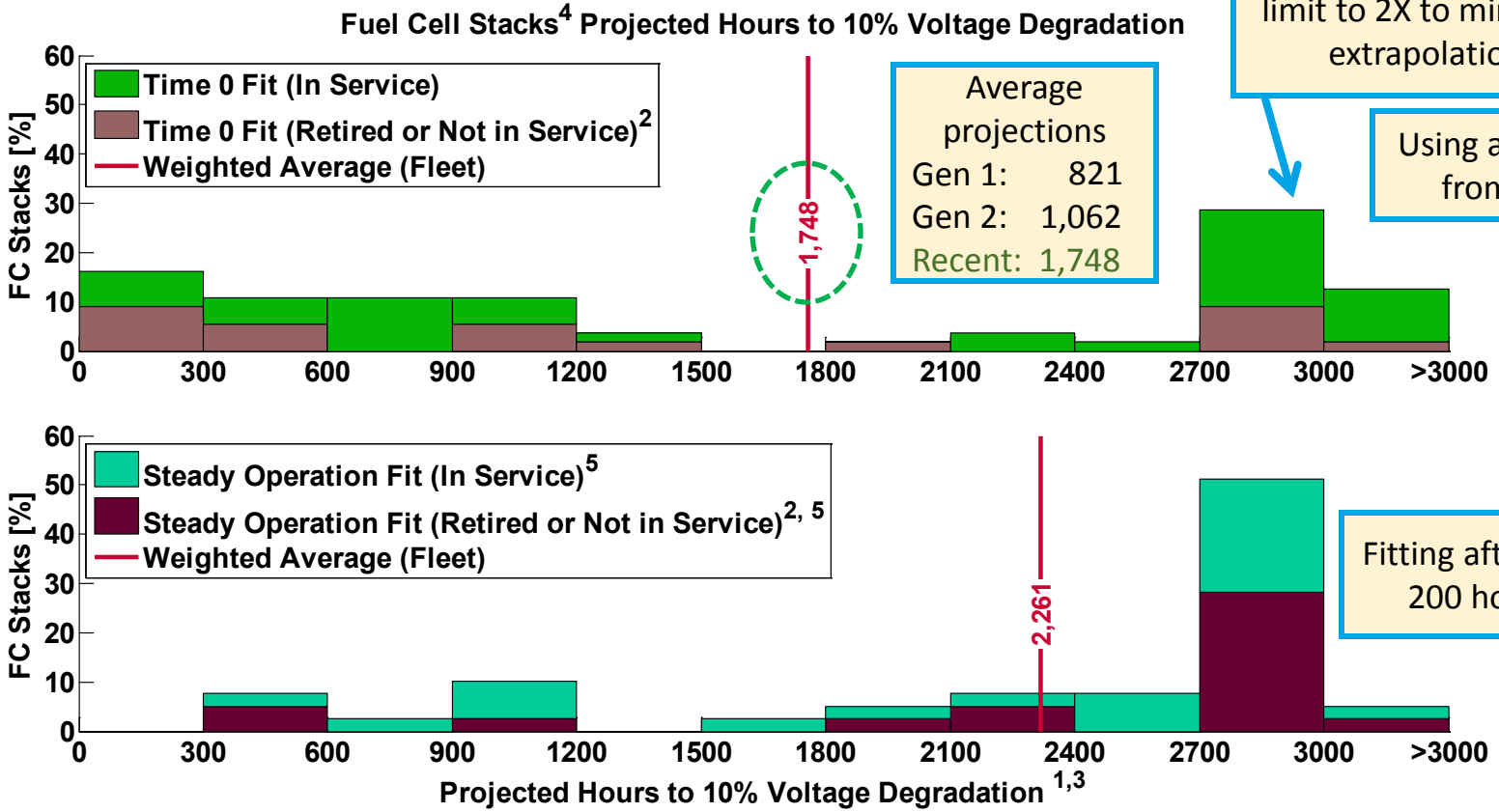


Some stacks operated over 1,400 hours, but half were still below 600 hours

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



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



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

Using all data from t0

Fitting after first 200 hours

1) Projection using field data, calculated at high stack current, from operation hour 0 or a steady operation period. Projected hours may differ from an OEM's end-of-life criterion and does not address "catastrophic" failure modes.
2) Indicates stacks that are no longer accumulating hours either a) temporarily or b) have been retired for non- stack performance related issues or c) removed from DOE program.
3) Projected hours limited based on demonstrated hours.
4) Only includes systems operating after 2009Q4.
5) Not all stacks have a steady operation fit which is calculated from data after 200 hr break-in period. The steady operation starting hour is an approximation of the period after initial break-in where degradation levels to a more steady rate.

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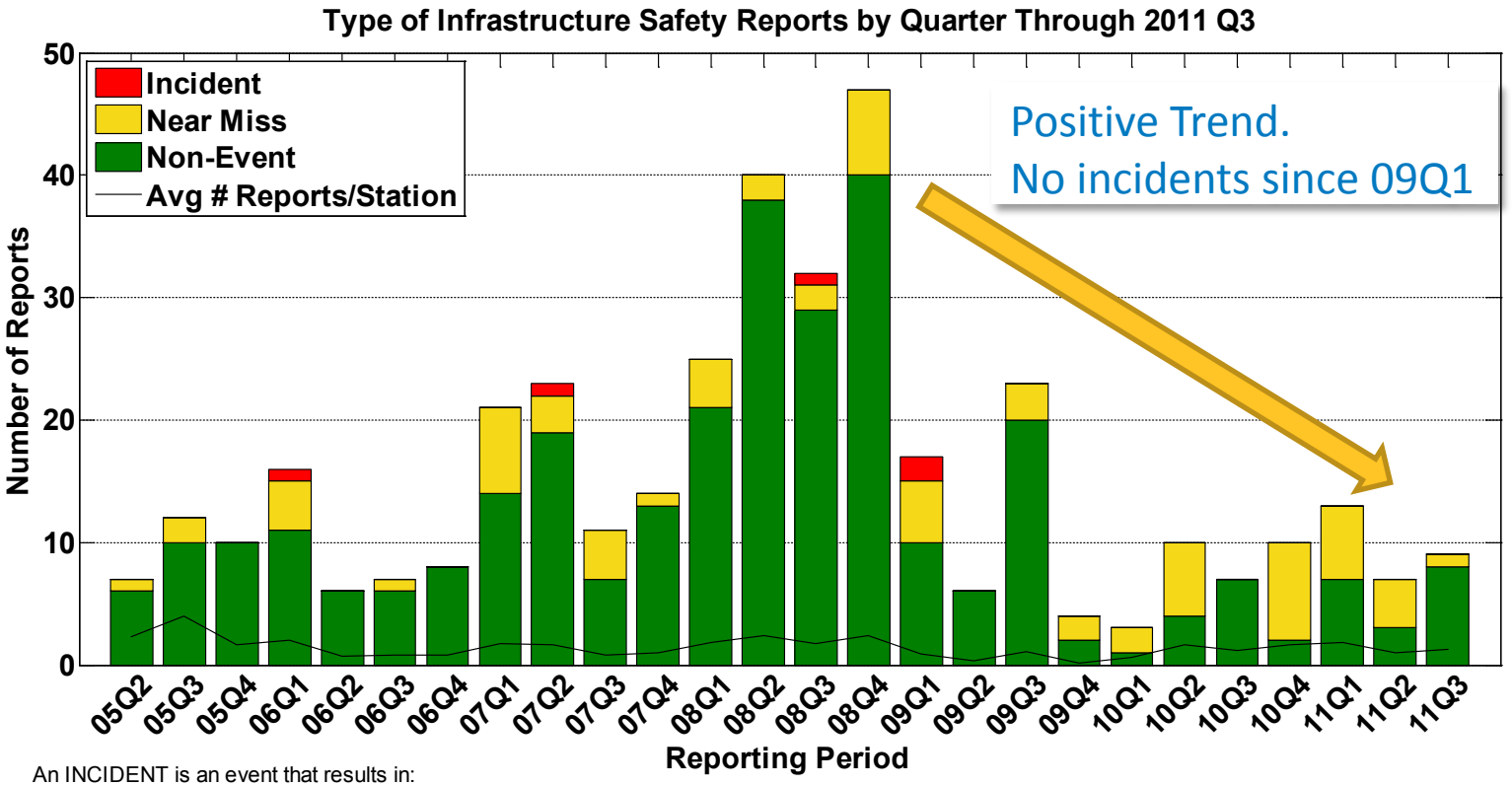
Infrastructure Safety



An INCIDENT is an event that results in:
- a lost time accident and/or injury to personnel
- damage/unplanned downtime for project equipment, facilities or property
- impact to the public or environment
- any hydrogen release that unintentionally ignites or is sufficient to sustain a flame if ignited
- release of any volatile, hydrogen containing compound (other than the hydrocarbons used as common fuels)

A NEAR-MISS is:
- an event that under slightly different circumstances could have become an incident
- unplanned H2 release insufficient to sustain a flame

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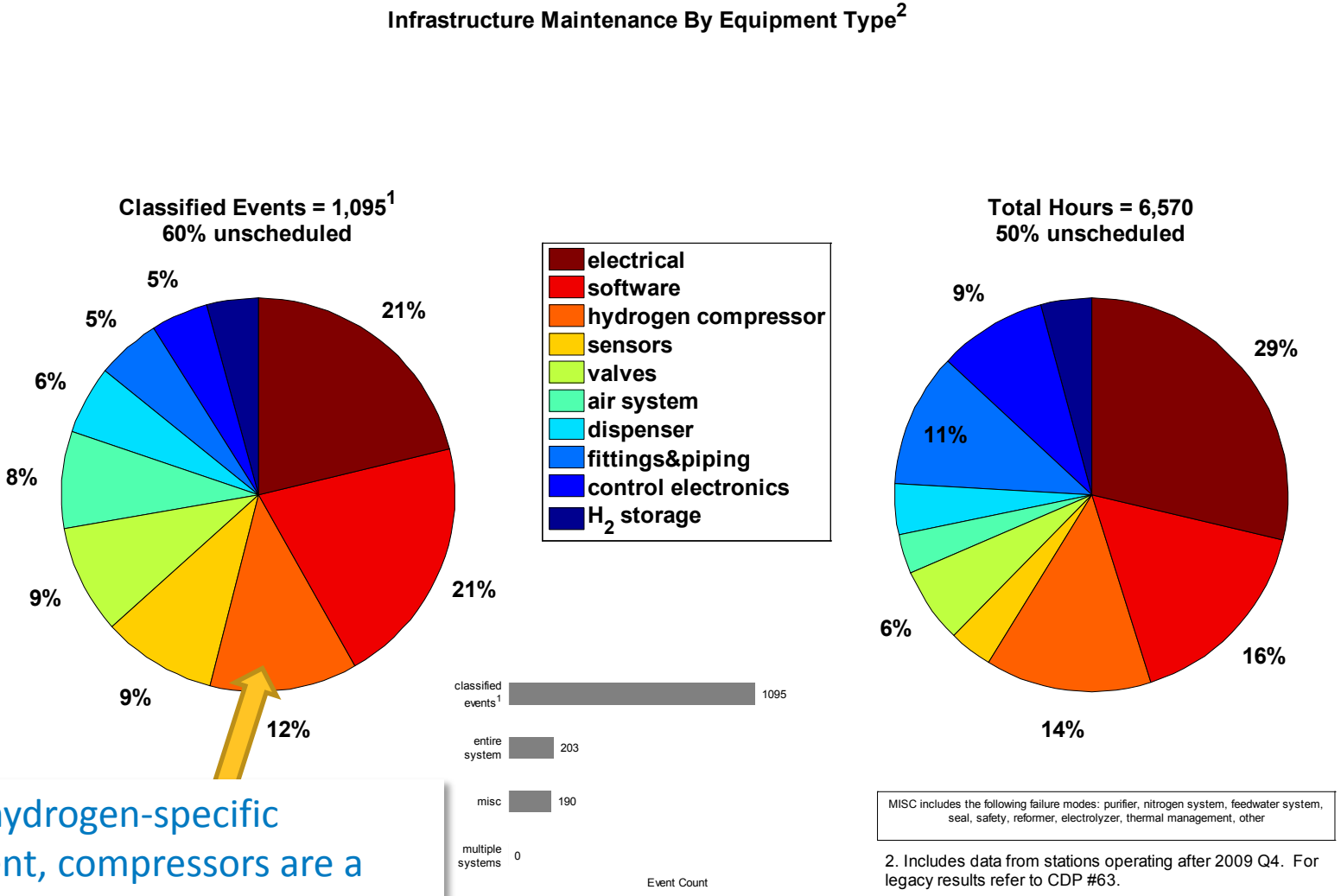
Infrastructure Maintenance: Equipment

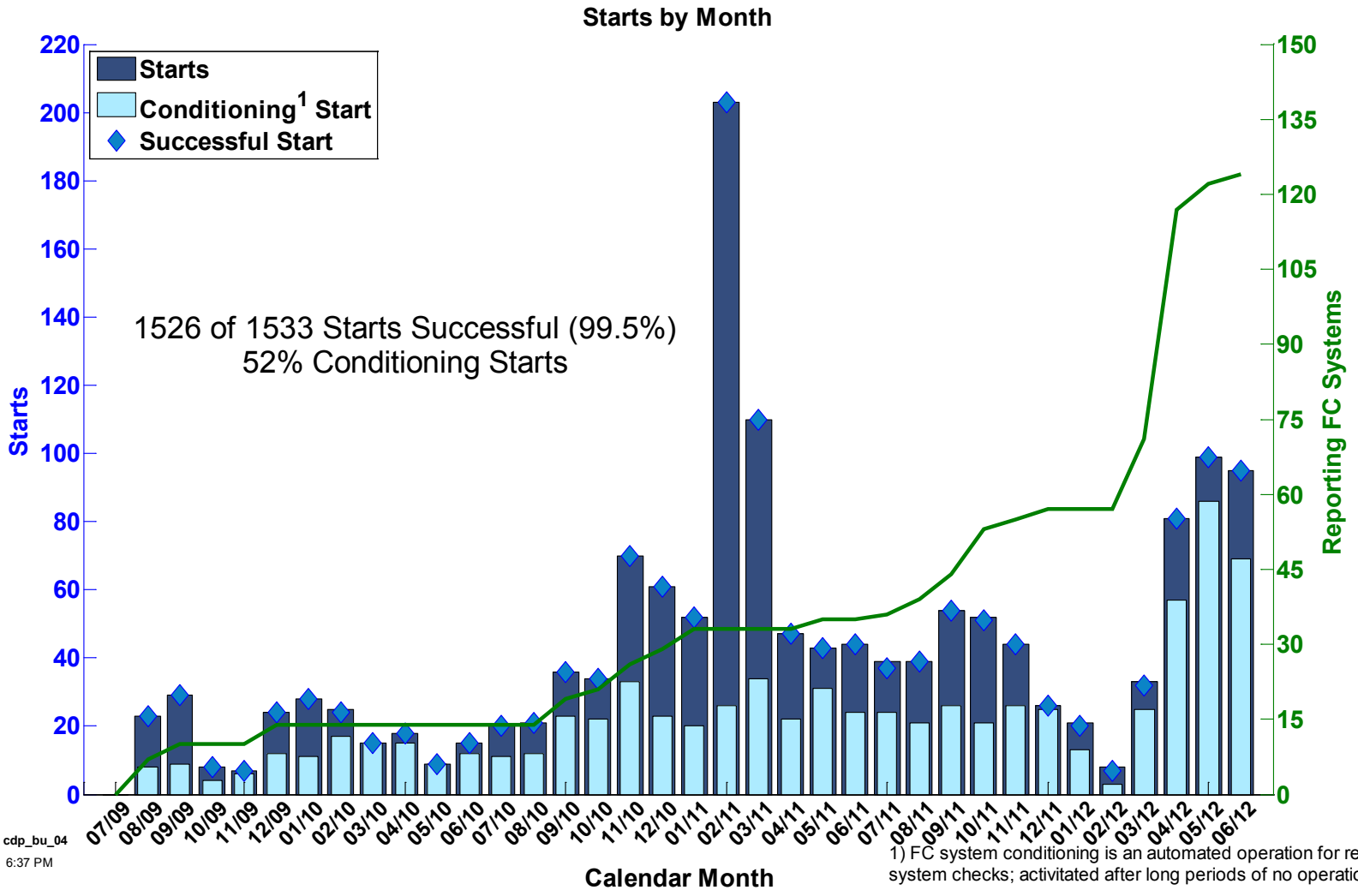


Among hydrogen-specific equipment, compressors are a leading cause of maintenance.

Backup Power

Reliability: 99.5% successful starts

BACKUP POWER



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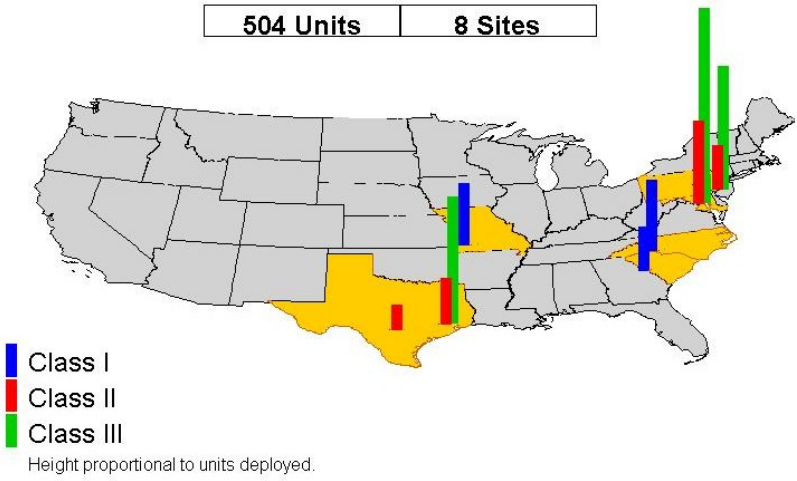
1) FC system conditioning is an automated operation for regular system checks; activitated after long periods of no operation.

Material Handling Equipment

MHE Operation Status

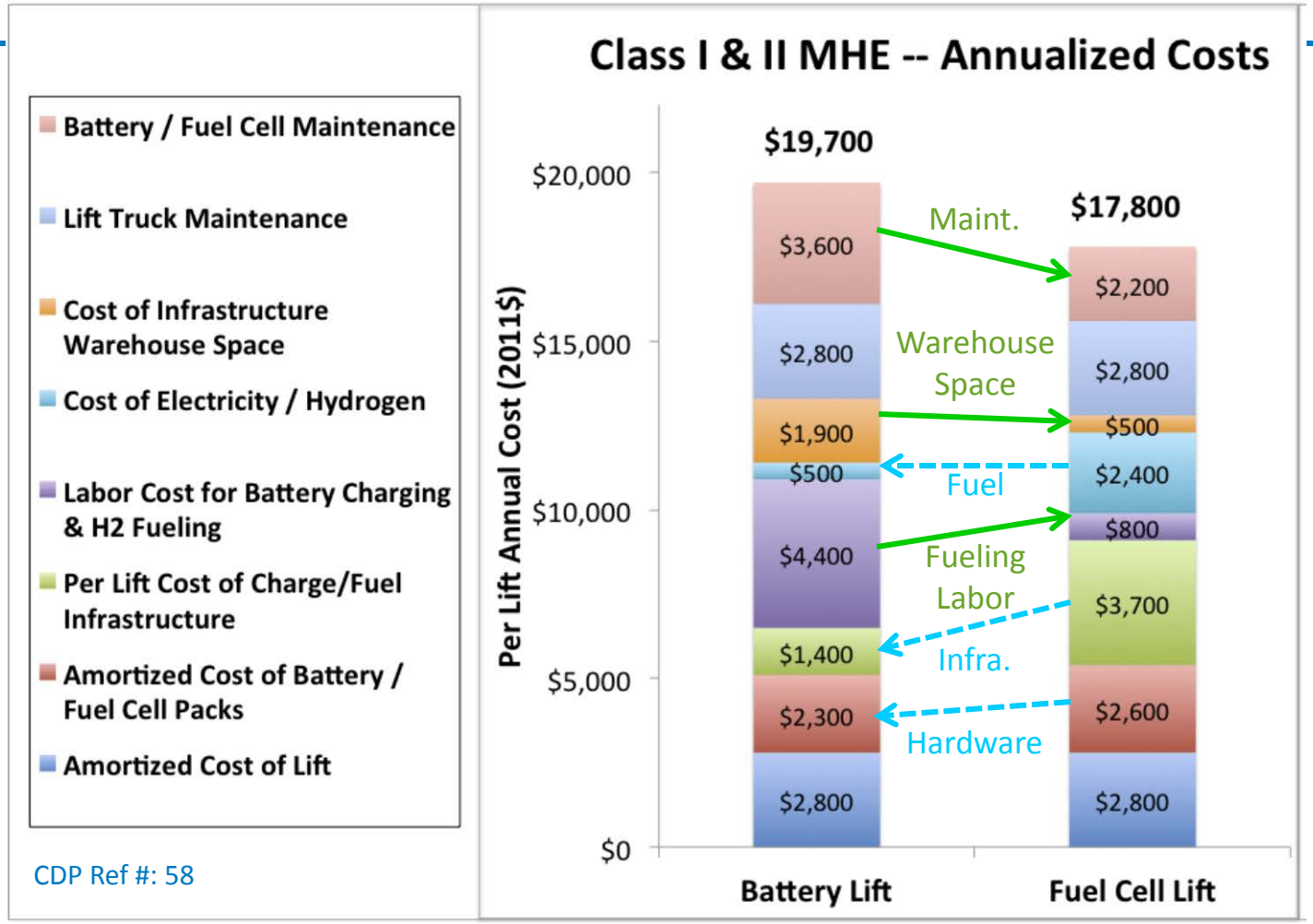
Key Operation Metric		CDPARRA-MHE-#
Units in Operation (100 Class 1, 62 Class 2, 172 Class 3)	490*	01
Hours Accumulated	1,248,384 hrs*	11
25% of FC Systems	> 5,260 hrs*	02
FC Systems Average > 6 hours Daily	66%*	24
Hydrogen Dispensed	141,500 kg*	04
Hydrogen Fills	197,991*	03
Average Fill Amount	0.6 kg/fill*	10
Average Fill Time	2.3 min/fill*	06
Average Op Time between Fill	4.7 hrs*	08



The majority of sites have delivered liquid hydrogen. 2 of the 8 sites are greenfield sites. 4 sites have more than one class of MHE in operation.

*Through June 2012

Annualized Total Cost of Ownership per Unit Identifies Key Cost Advantages are Dependent on Deployment Size



CDP Ref #: 58

Analysis inputs are averages per category, some key inputs are:

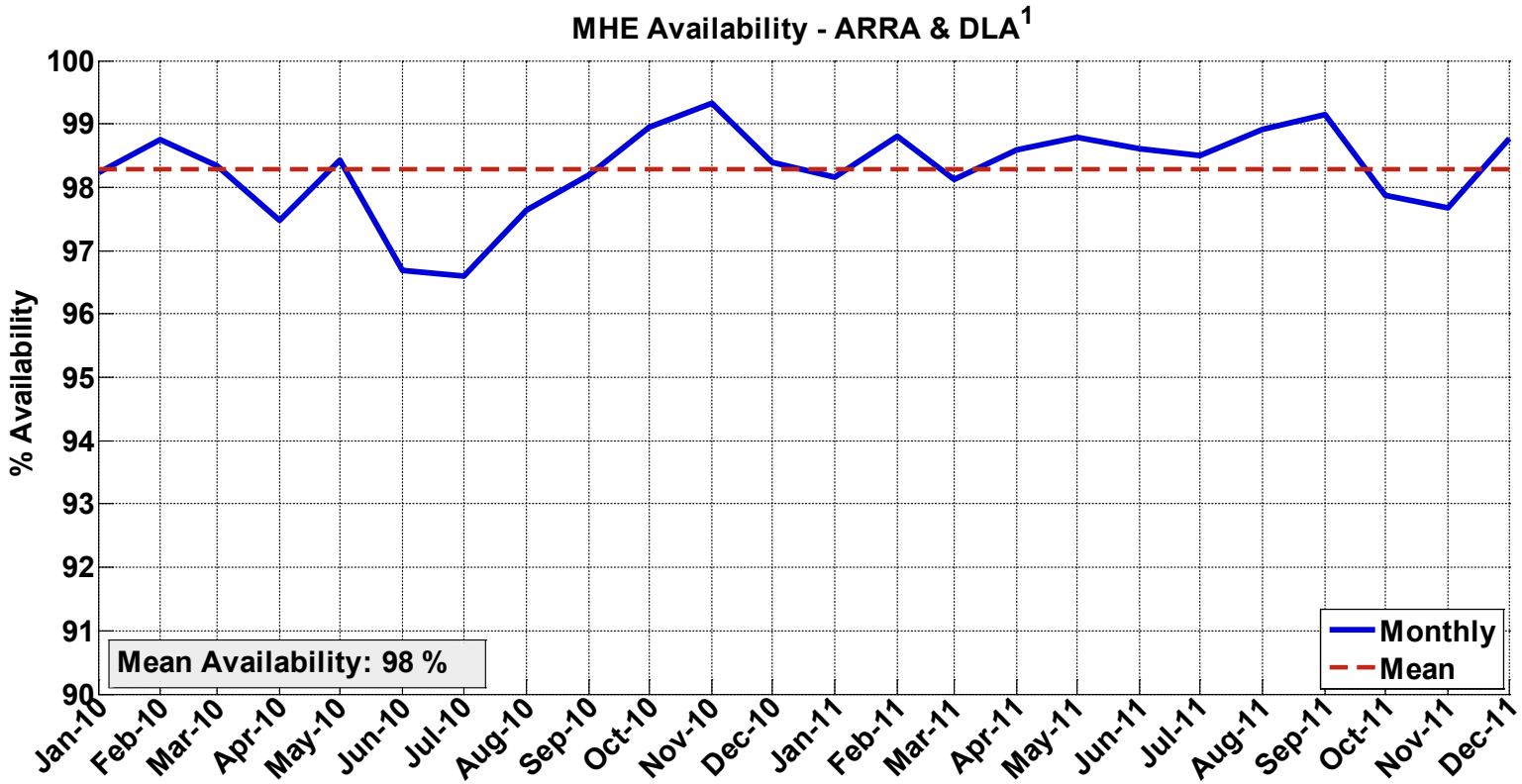
- 58 FC lifts
- 333 days per year, 2.5 shifts per day (2,100 pedal hours per year)
- 3 min per hydrogen fill & 10 min per battery change out

Class III Annualized Cost

- $11,700 FC
- $12,400 Battery

Results assume replacements as needed and do not reflect technology generation improvements or other productivity improvements such as constant power, emissions, and cold environment. FC costs include current tax credit of $3,000/kW or 30% of purchase price. Data source: ARRA & DLA project partner questionnaire & fuel cell performance data.

MHE Availability



1. Availability is calculated as follows:
   Availability starts at 100% for each vehicle on each calendar day.
   If the vehicle has a maintenance record on a given day, unavailable hours are subtracted from availability.
   The number of unavailable hours is calculated according to the following schedule:
   A. Unavailable hours = 21 hours if maintenance hours is blank or > 6 hours.
   B. Unavailable hours = if maintenance hours are between 4 and 6 hours.
   C. Unavailable hours = the actual maintenance hours if it is less than 4 hours.
   D. If maintenance hours are > 21 , the rules A-C above are applied recursively to any remainder above 21 hours.

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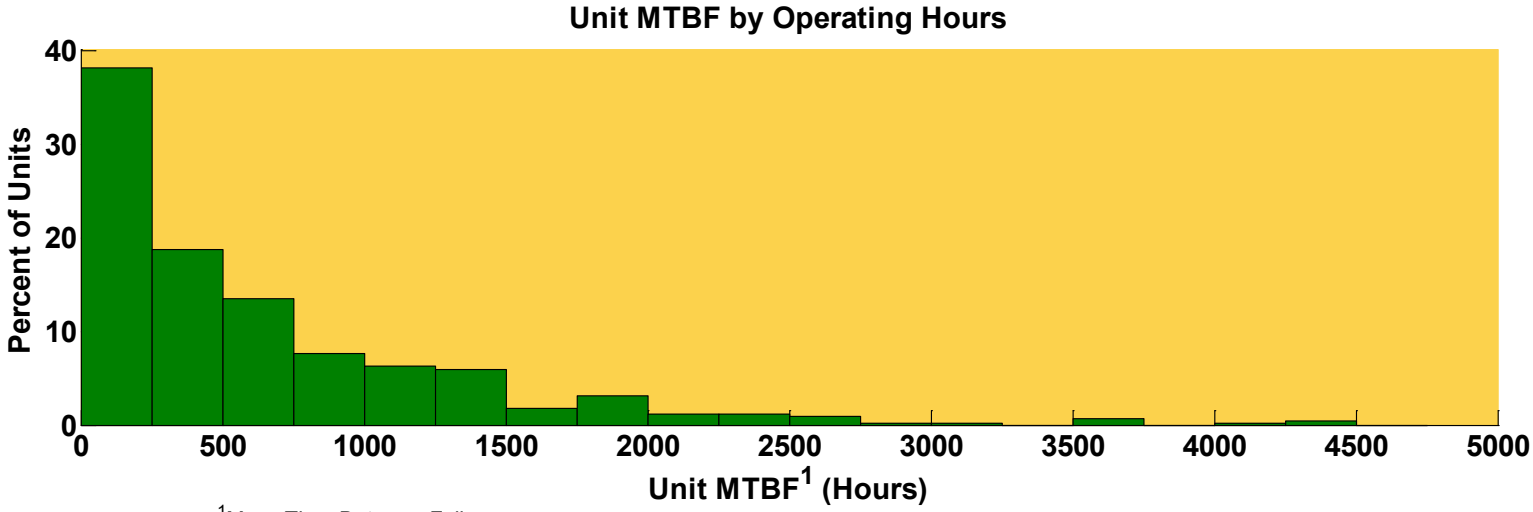
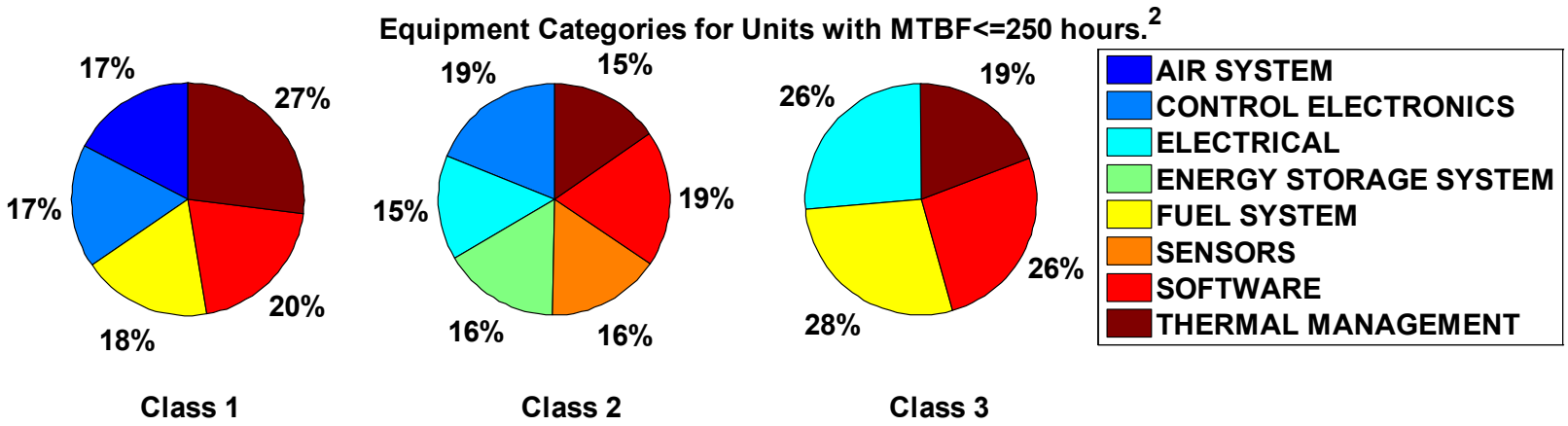
Reliability - Fuel Cell System



[1]Mean Time Between Failure



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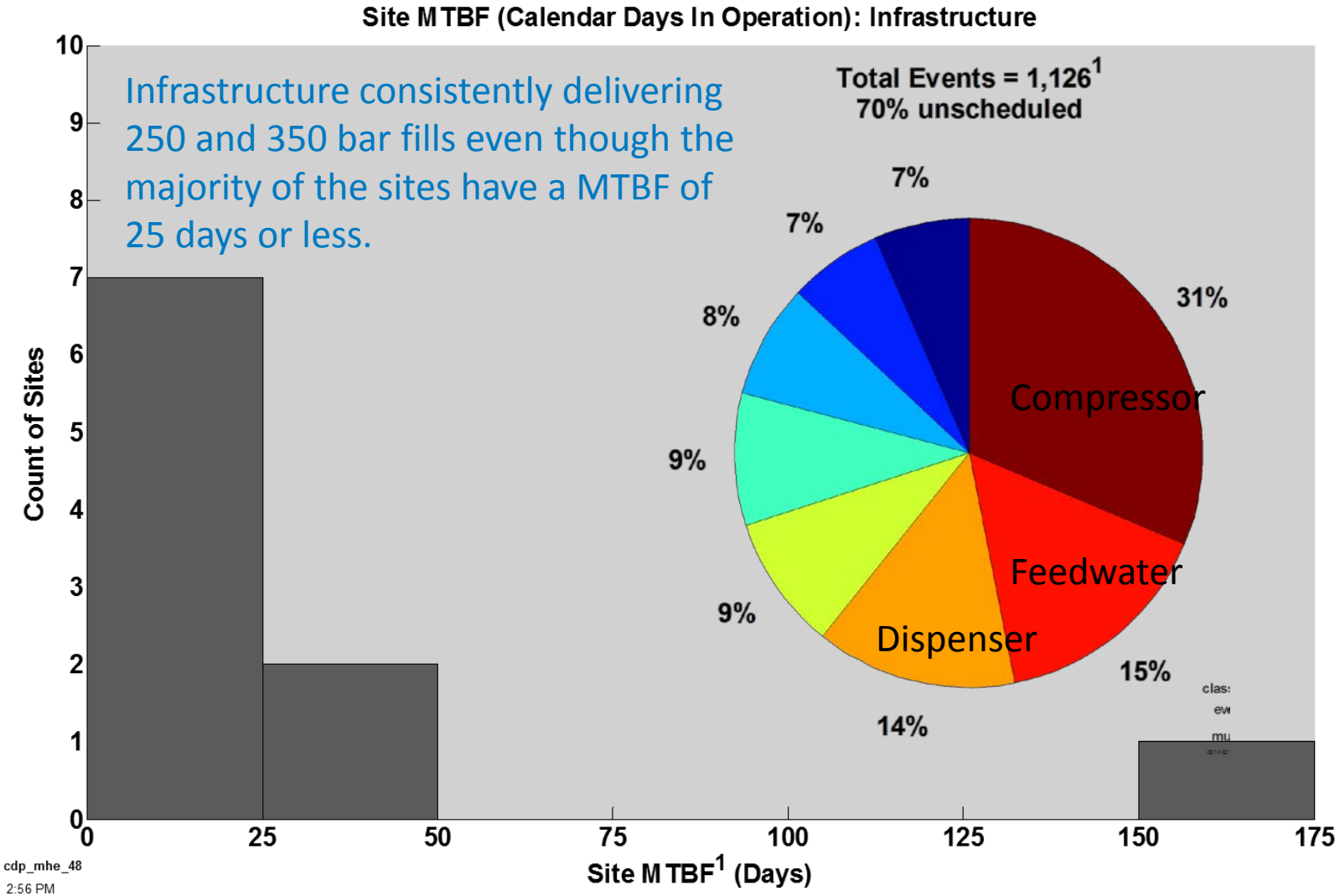
[2] Categories representing <10% of the total are not shown

Reliability - Infrastructure



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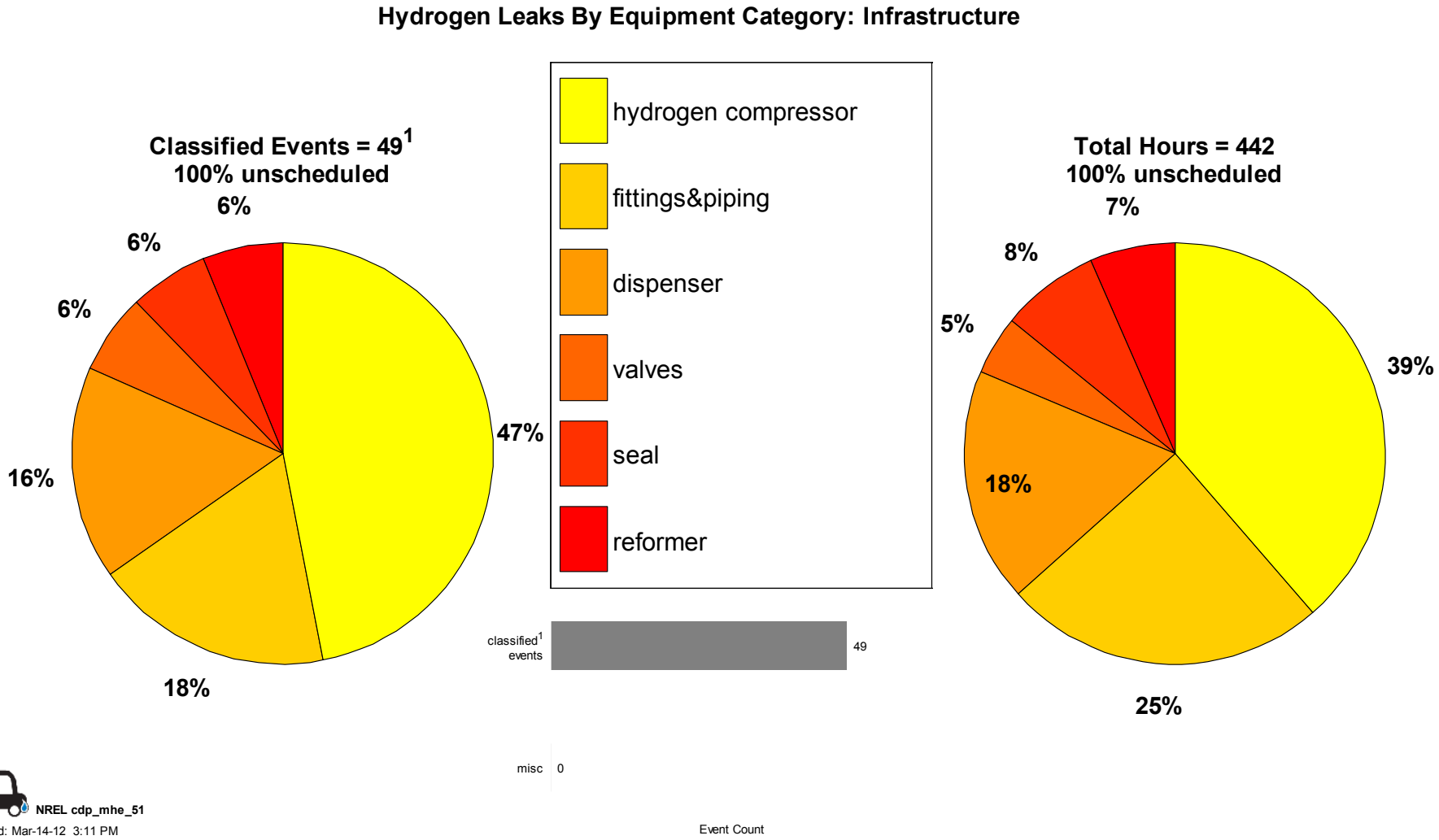
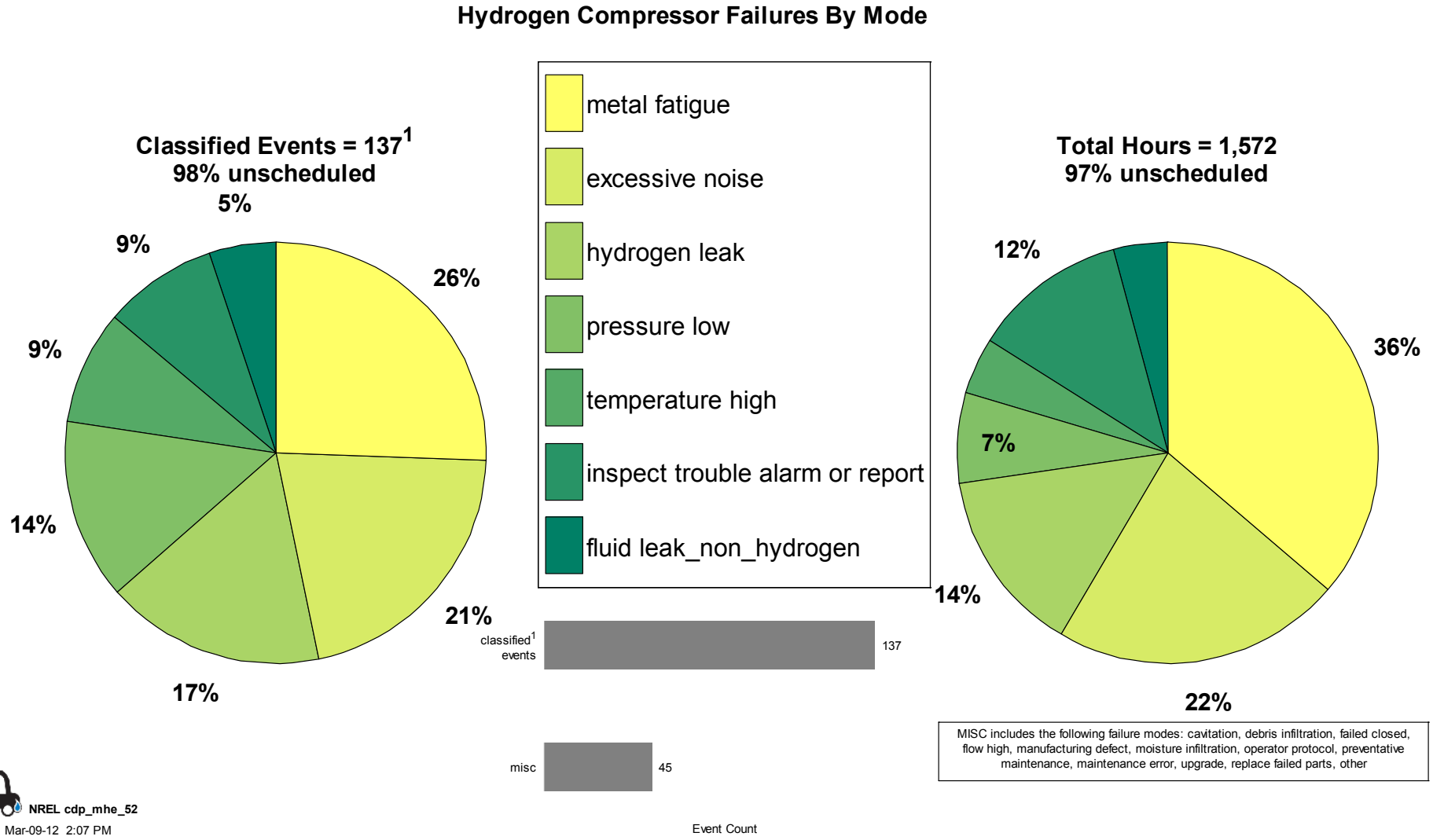
1. Cumulative Mean Time Between Failure

Deep Dive: Hydrogen Leaks



Deep Dive: Hydrogen Compressors



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Hydrogen Compressors: Improving Reliability

FORKLIFTS

- DOE & NREL have begun an accelerated test program to evaluate H_2 compressor failures & solutions in more detail.
- NREL provides the test facilities and labor. Compressor partners provide test articles.

Technical Summary – *What We've Learned*

Light Duty Vehciles

- 183 Vehicles:
  - 154,000 hours
  - 3.6M miles
  - 500K trips
- 25 Stations:
  - 152,000 kg produced/dispensed
  - 33K fuelings
- Met DOE target of 2000 hours stack durability
- Met DOE target of 250 mile driving range.

Technical Summary – *What We've Learned*

Fuel Cell Backup Power

- Operating reliability in 15 states with 99.5% successful starts.
- Maximum continuous run time of 29 hours due to an unplanned grid outage.

Fuel Cell Material Handling Equipment

- Operating with an average availability of ~98% at 8 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 cost for refueling labor and infrastructure space but much greater cost for hydrogen infrastructure and fuel.

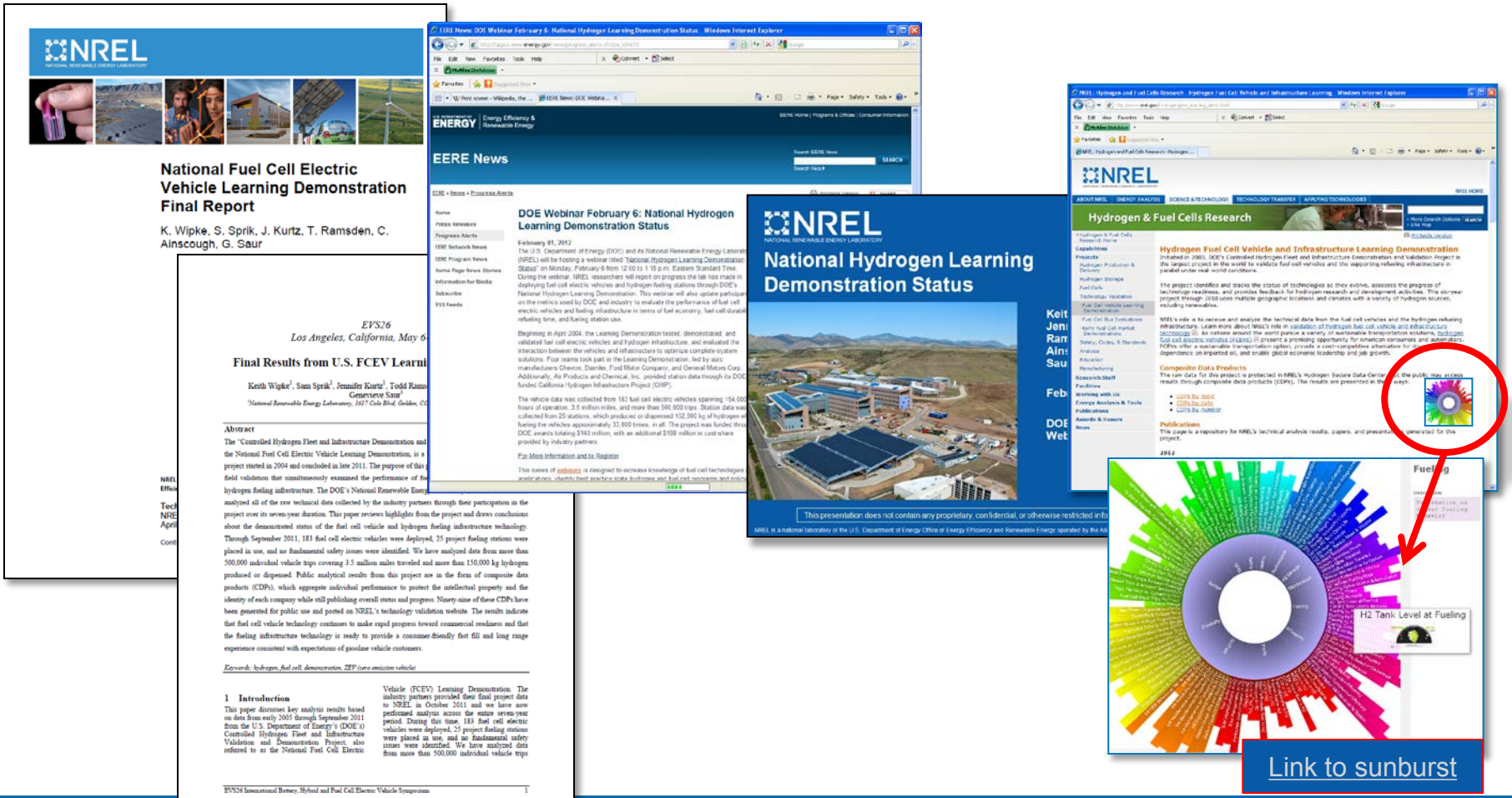
Aggregated data showcases performance over the last two years in MHE and backup power.

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.

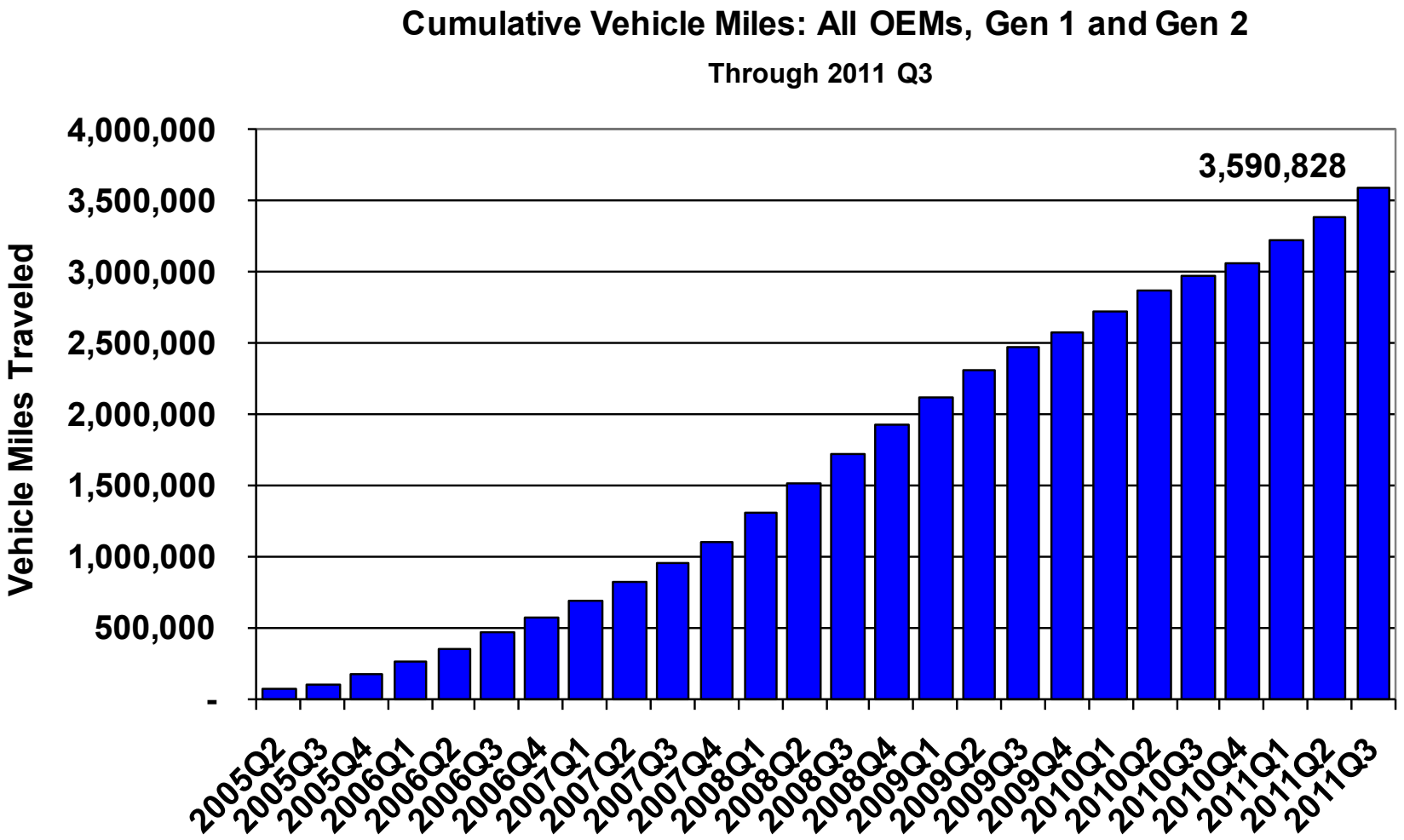
More information available

- www.nrel.gov/hydrogen/proj_tech_validation.html
- or search for “NREL CDP”



Backup Slides

Cumulative Mileage



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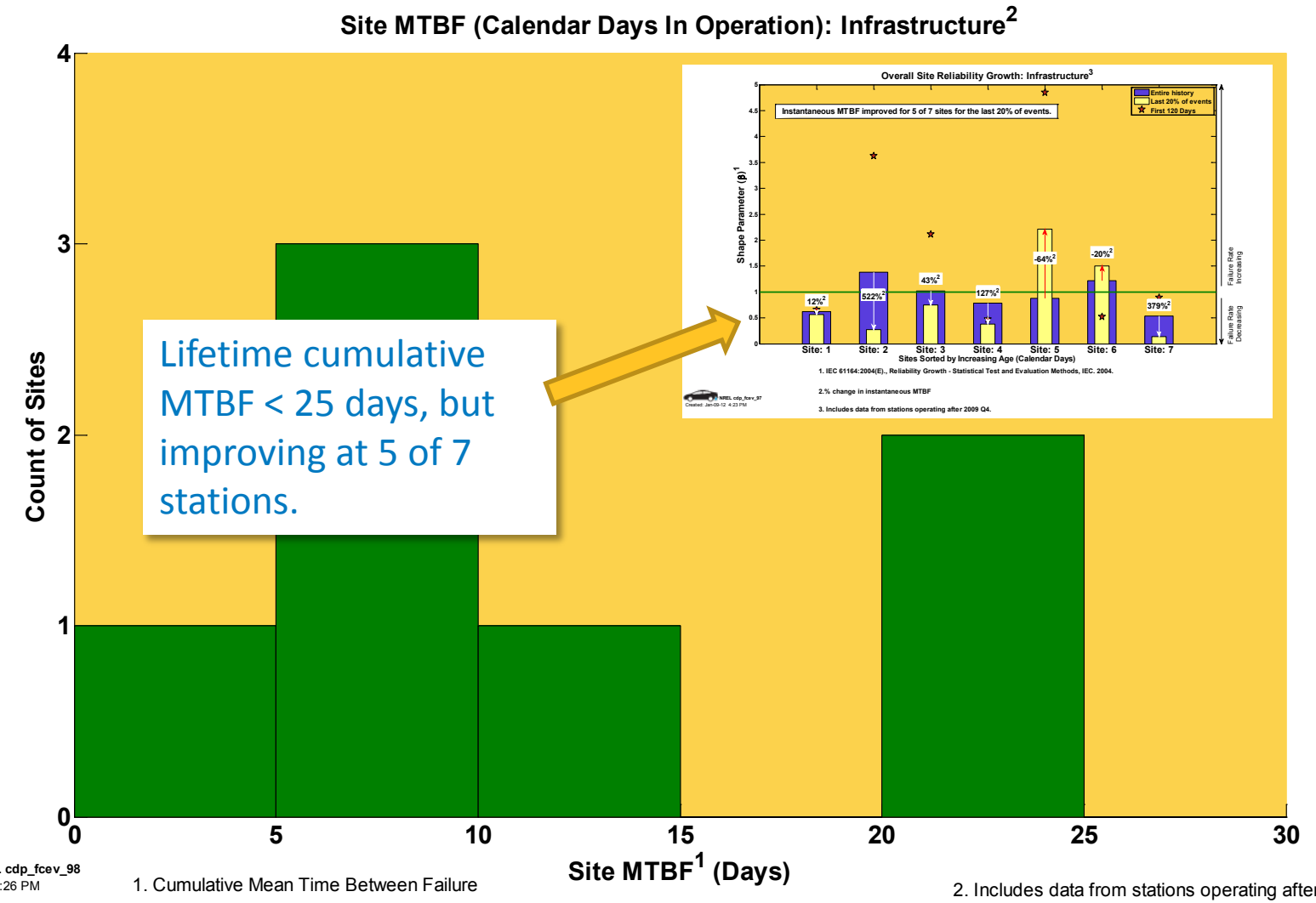
Infrastructure Maintenance: MTBF



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1. Cumulative Mean Time Between Failure

2. Includes data from stations operating after 2009 Q4.

Cost of Ownership: Backup power

BACKUP POWER

Gathering data on:

- Site Description
- System Description
- System Requirements
- Capital Cost
- Operating & Maintenance Cost
- Operating Lifetime

for fuel cells, batteries, and generators

	Fuel Cell*	Diesel	Battery
Reliability	+	o	+
Capital Cost ($/kW)	-	+	++
Extended Run Time	++	++	--
Emissions	++	-	++
Noise	+	+	++
Environmental	~	-	~
Weight	+	-	-
Efficiency	+	-	++
Annual Fuel Cost	+	-	++
Annual Maintenance Cost	+	-	++
Maintenance Frequency	++	-	?
Refurbishment	+	+	--
Conditioning Tests	+	-	~
Operation Lifetime	+	++	--

*Tax credit $3,000/kW or 30% total