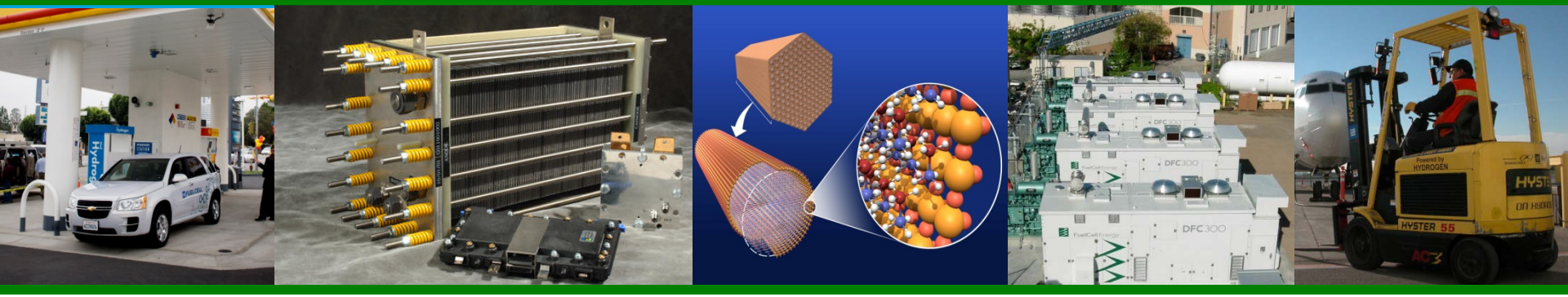
U.S. DEPARTMENT OF ENERGY



Technology Validation Program Area
-Plenary Presentation -

Jason Marcinkoski

Fuel Cell Technologies Office

2015 Annual Merit Review and Peer Evaluation Meeting

June 10, 2015

Goals and Objectives

OBJECTIVES

By 2019:

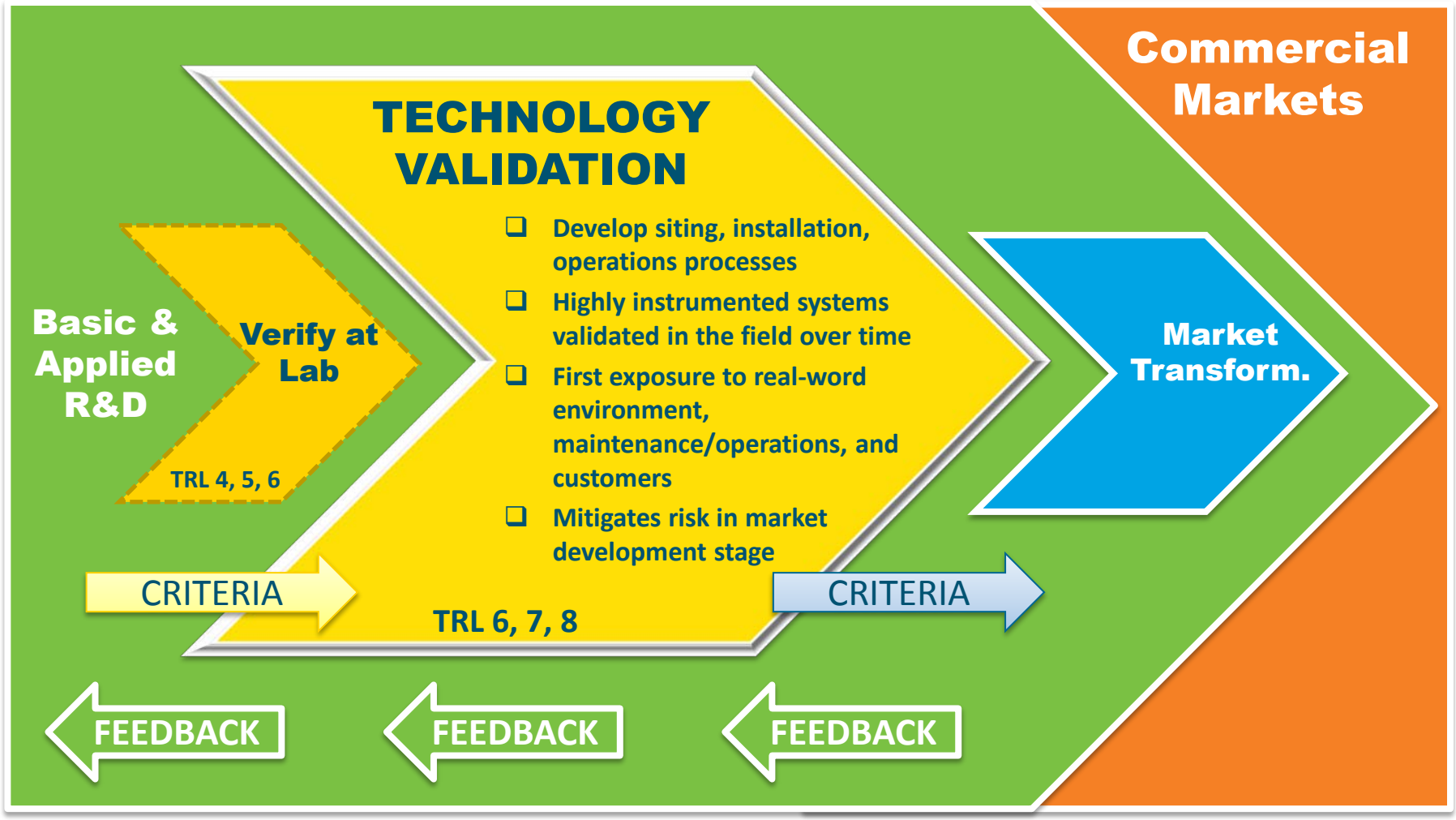
- ❑ Validate hydrogen fuel cell electric vehicles with greater than 300-mile range and 5,000 hours fuel cell durability
- ❑ Validate a hydrogen fueling station capable of producing and dispensing 200 kg H_2/day (at 5kgH_2/3 min; 700 bar) to cars and/or buses

By 2020:

- ❑ Validate large-scale systems for grid energy storage that integrate renewable hydrogen generation and storage with fuel cell power generation by operating for more than 10,000 hours with a round-trip efficiency of 40%

GOAL: ***Validate fuel cell systems in transportation and stationary applications as well as hydrogen production, delivery and storage systems. Assess technology status and progress to determine when technologies should be moved to the market transformation phase.***

Strategy


Commercial Markets
TECHNOLOGY VALIDATION
Basic & Applied R&D
Verify at Lab
TRL 4, 5, 6
Develop siting, installation, operations processes
Highly instrumented systems validated in the field over time
First exposure to real-word environment, maintenance/operations, and customers
Mitigates risk in market development stage
Market Transform.
CRITERIA
CRITERIA
TRL 6, 7, 8
FEEDBACK
FEEDBACK
FEEDBACK

Current Targets & Status

FUEL CELL VEHICLES	2015 Status	2020 Goal
On-road Fuel Economy (mpgge)	50 - 55	N/A
Durability (hrs)	3,900	5,000
FC System Peak Efficiency	60	65

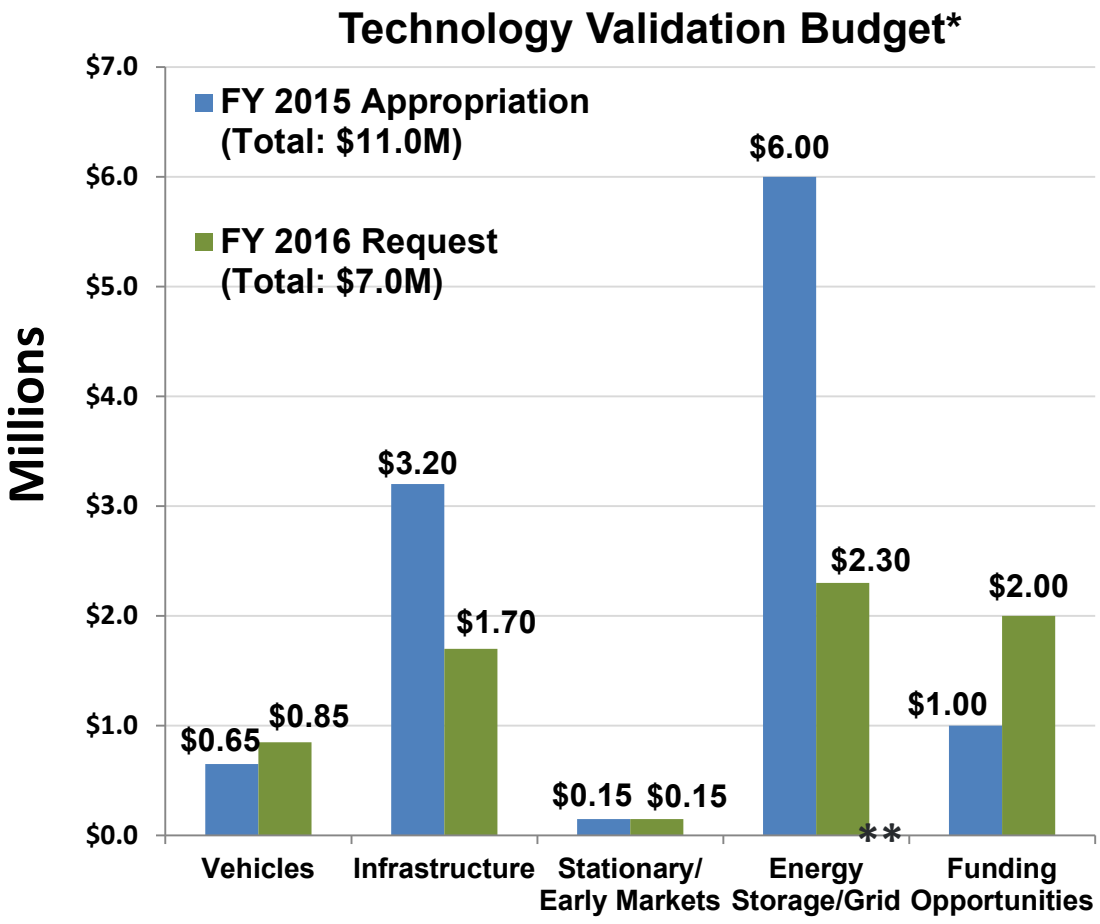
FUEL CELL BUSES	2015 Status	2016 Goal	Ultimate Goal
Durability (hrs)	1,000 – 19,000	18,000	25,000
Miles Between Road Call (Bus/ FC System)	4,256/ 18,896	3,500/ 15,000	4,000/ 20,000
Fuel Economy (mpdge)	7.26	8	8
Bus Availability (%)	70	85	90

H_2 STATIONS	2015 Status	2020 Goal
Fueling Rate (kg/min)	0.60	1.5

COMMERCIAL POWER (100 kW – 3 MW)	2015 Status	2020 Goal
Durability (hrs)	40,000 – 80,000	65,000
Availability (%)	95	98
Electrical Efficiency, Lower Heating Value (%)	42 – 47	48

Budget

FY 2016 Request = $7.0M
FY 2015 Appropriation = $11.0M



EMPHASIS

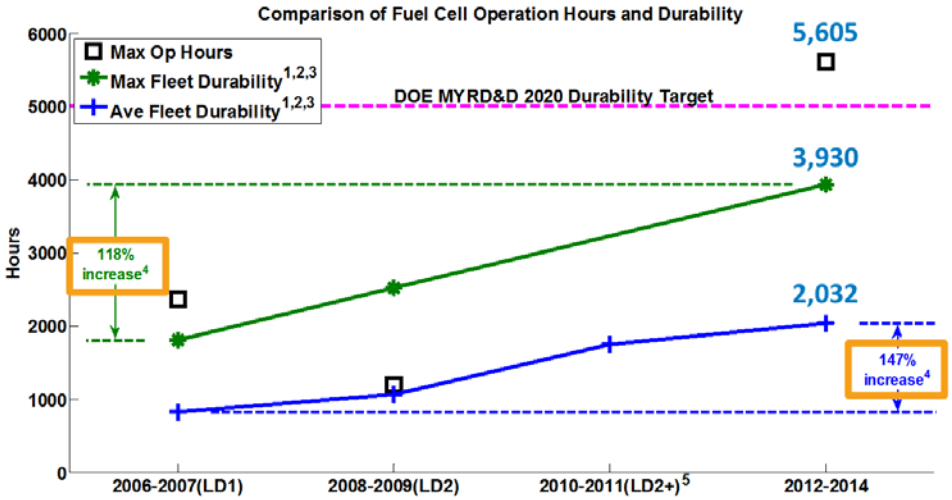
- **VEHICLES**
  - ❑ Light-duty Vehicles
  - ❑ Medium-duty Trucks* (collaboration with Market Transformation)
  - ❑ Buses (collaboration with DOT)
- **INFRASTRUCTURE**
  - ❑ Fueling Station Data
  - ❑ Compressor Reliability Testing
  - ❑ Cryo-compressor Testing*
  - ❑ Mobile Refuelers
  - ❑ Station Operational Status System
  - ❑ Hydrogen Station Equipment Performance Device*
- **STATIONARY/EARLY MARKETS**
- **GRID INTEGRATION/ENERGY STORAGE***

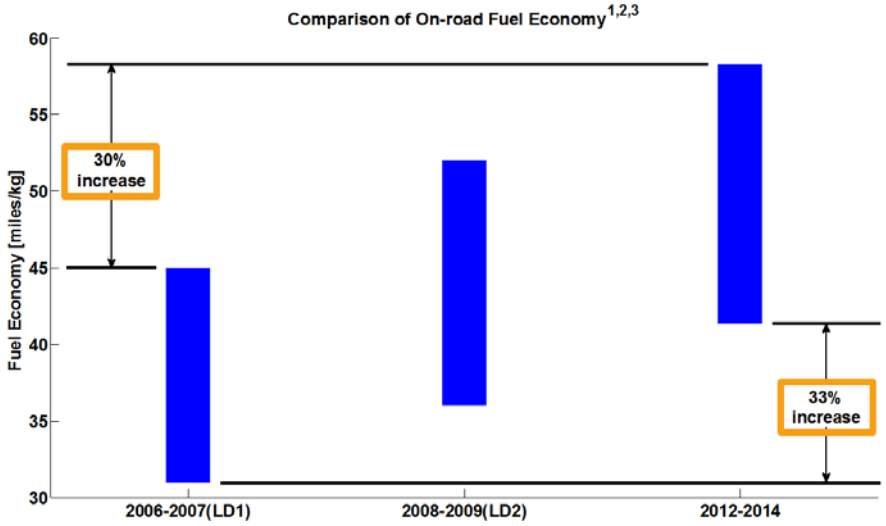
* Projects that include Technology Validation funding for equipment or development.
Many Technology Validation projects validate equipment/technologies funded by industry, states, U.S. agencies, or other DOE programs.
** Lab call to be issued under Energy Storage/Grid activities.

ACCOMPLISHMENTS: Fuel Cell Vehicles

Current Status*

- ✓ **3,930 hrs** max fleet avg. durability
- ✓ **5,605 hrs** max fuel cell stack operation
- ✓ **50-55 mi/gge** avg. **on-road** vehicle fuel economy for >50% of vehicles
- ✓ **~53 mi/gge** median window sticker vehicle fuel economy
- ✓ **2,413,340 mi** traveled (**~45% of vehicles** traveled between 25,000 and 50,000 miles)
- ✓ **79,468 hrs** of total fuel cell stack operation





*** Results are for vehicle model years 2005 – 2012 and do not include data previously reported in the Learning Demonstration (LD). Total miles traveled is over 5.7 million from LD and current projects. Not all metrics are necessarily met simultaneously.**

ELECTRICORE
POWERING THE FUTURE

TOYOTA

HONDA

NISSAN GROUP OF NORTH AMERICA

NISSAN

HYUNDAI

MERCEDES-BENZ

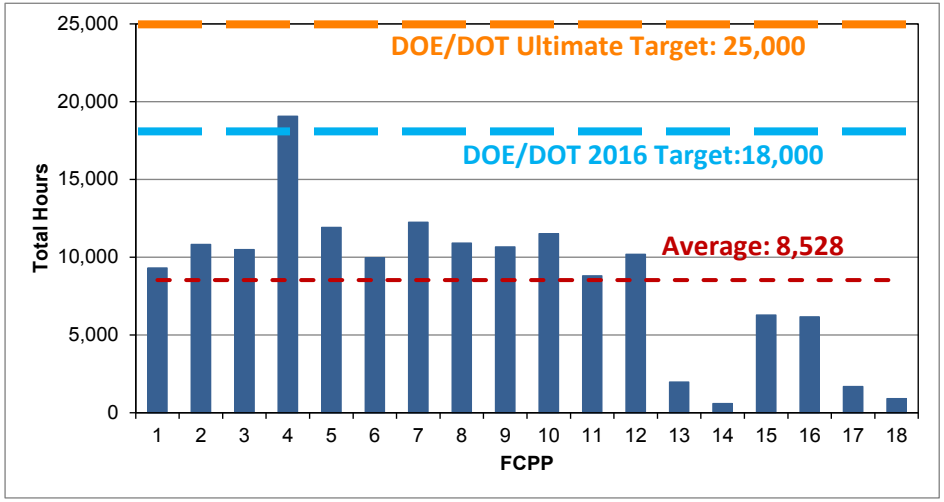
GM

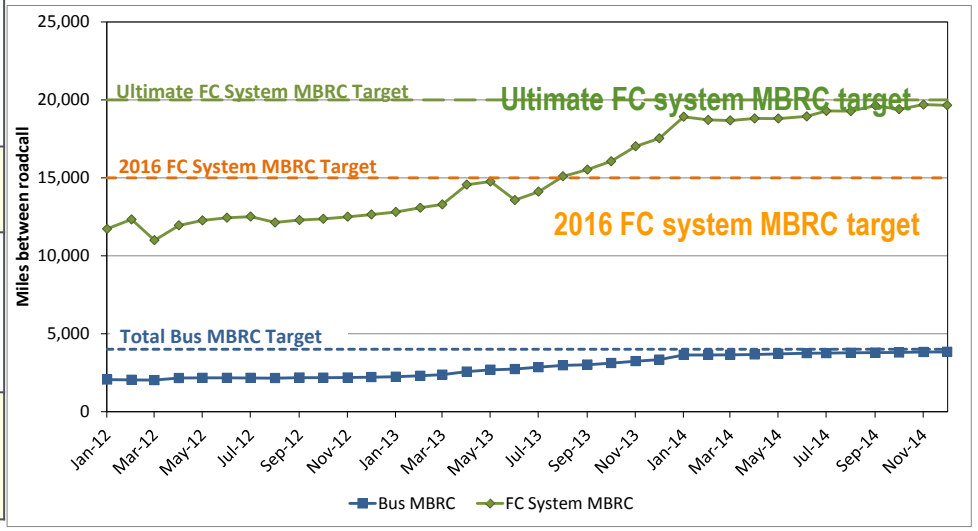
Steady progress has been demonstrated over four evaluation periods with improvements especially in fuel cell durability, range, and fuel economy.

ACCOMPLISHMENTS: Fuel Cell Buses

Current Targets	Units	Current Status	2016 Target	Ultimate Target
bus lifetime	yrs/ mi	5/ 100,000	12/ 500,000	12/ 500,000
powerplant lifetime	hrs	1,000 – **19,000**	18,000	25,000
bus availability	%	70	85	90
roadcall frequency (bus/ FC system)	mi between road call	**4,256/ 18,896**	3,500/ 15,000	4,000/ 20,000
oper. time	hrs per day/days per week	19/7	20/7	20/7
maint. cost	$/mile	**0.67**	0.75	0.40
fuel econ.	mi per diesel gallon equiv.	7.26	8	8
range	mi	220 - **310**	300	300

*** MBRC: Mean Time Between Road Call**





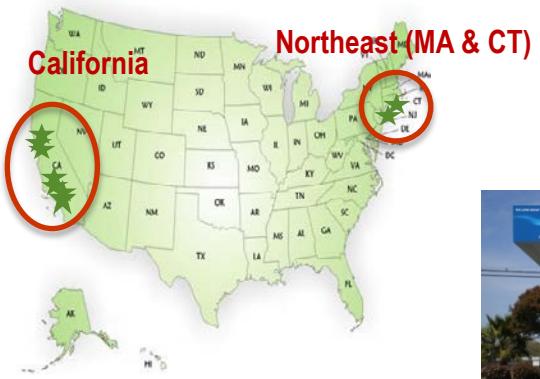
Top FCPP > 19,000 hrs, surpassing DOE/DOT target (67% of FCPPs > 8,000 hrs). MBRC* surpasses 2016 target, approaching ultimate target.

ACCOMPLISHMENTS: Hydrogen Stations

10 H_2 Stations*

- ✓ **62,784 kg** cumulative H_2 dispensed
  ~17,000 kg dispensed in 2014
- ✓ **5.6 min** avg. fill time
  49% of fills less than 5 min
  20% of fills less than 3 min
- ✓ **0.6 kg/min** avg. fueling rate
  16% > 1 kg/min

* ***Data for 2009Q1-2014Q4***



California State University—Los Angeles (CSULA)

- ✓ First in U.S. to receive seal of approval for sale of hydrogen on per kg basis as of January 2015; up to 242 kg H_2/month sold
- ✓ Installed power and flow meters, buffer tanks--data collection ongoing

Proton Energy (Proton OnSite)

- ✓ SunHydro#1 station (Wallingford, CT)
  - ❑ Data monitoring and energy measurements ongoing;
  - ❑ 57bar stack and system built and tested
- ✓ SunHydo#2 station (Braintree, MA) designed and fabrication well underway

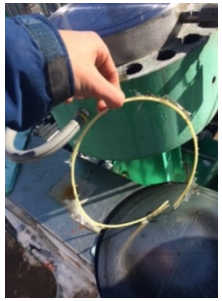
Gas Technology Institute (GTI)

- ✓ **West Sacramento:** Station (LH2; ionic compression) commissioned December 2014; instrumentation installed and data collection begun
- ✓ **San Juan Capistrano:** Permits granted; construction to begin mid-2015
- ✓ **Remaining 3 Sites:** Equipment being fabricated; construction dates will likely depend on permitting

First commercially sold hydrogen in the U.S.; new hydrogen stations coming online.

ACCOMPLISHMENTS: Hydrogen Compressor Evaluation

- ✓ Four compressors in operation at NREL
  - ❑ DUT1: Extensive data collection and 20 hrs/day testing
  - ❑ DUT2-4: Failure data and operating hours
- ✓ Performance and reliability data compared to data collected in field (through composite data products)
- ✓ Deep dive failure analyses performed

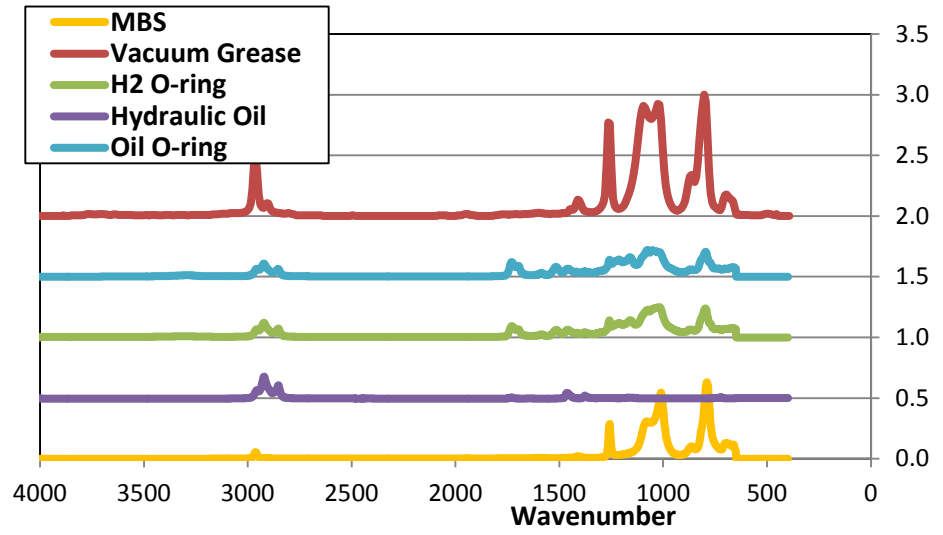


Contaminant Analysis

- ❖ Siloxane harmful to FCs
  - ▪ Membrane embrittlement
  - ▪ Crossover
- ❖ Suitable replacement chemical (with minimal effects on FC) determined.

Oper. Time	Start/ Stops	H_2 Compr.	# Major Failures	MTBF	Calc. Flow Rate	Avg. Eff.
753 hrs	81	1,808 kg	4	49 days	3.7 kg/hr	3.54 kWh/kg

Fourier Transform Infrared Spectroscopy Attenuated Total Reflectance



Key Findings

- ❑ Compressor performance and reliability--consistent power consumption (with varying pressure and temperature)
- ❑ Catastrophic seal failure detected preemptively—alarms set; early action may prevent contamination/downtime
- ❑ Seal weakness is main failure mechanism--repairs of common failures expensive (up to $1,200) and time consuming (up to 6 weeks parts lead time)

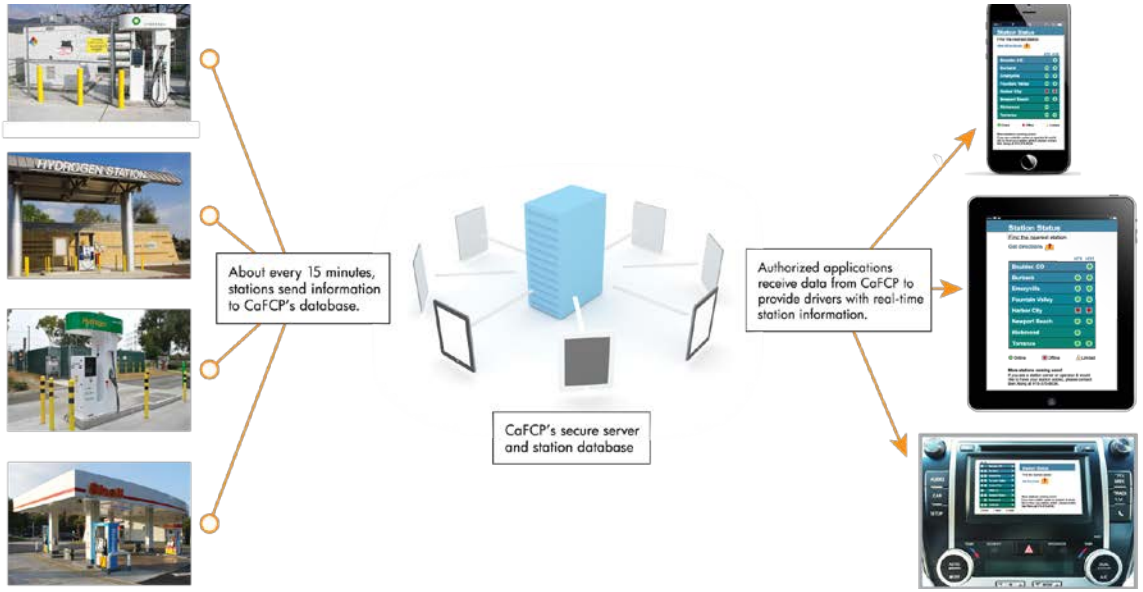
Accelerated testing to reproduce component failures, correlated to real-world usage with statistical methods.
Compressors account for 1/3 of maintenance hours at stations.

ACCOMPLISHMENTS: Cryogenic Pressurized Hydrogen Storage and Delivery

- ✓ Built and pressure tested first cryogenic compatible, thin-lined (1.8 mm) pressure vessel
  - ❑ 81% volume ratio at 700 bar (vs. 70% conventional vessels)
  - ❑ Demonstrated cryogenic strength
- ✓ Instrumented LH2 pump (electric, vent, temperature)
- ✓ Built pressure vessel test facility
- ✓ Obtained DOE/LLNL operational approvals
- ✓ Will start cycle testing of prototype pressure vessels (scheduled for September 2015)

Cryogenic pressurized storage has potential to meet DOE goals. Critical issues such as maximum system density, scalability, vessel and pump durability are being addressed.

ACCOMPLISHMENTS: CaFCP--Station Operational System Status (SOSS)



ONLINE
- Station can deliver SOC > 90%
- Boost compressor online
- High pressure storage online
- Chiller online
- H2 source online
- POS online

LIMITED
- Station can still deliver fuel but SOC<=90%
- Boost compressor offline
- High pressure storage offline
- Chiller online
- H2 source offline
- POS online

OFFLINE
- Station cannot deliver fuel
- Boost compressor offline
- High pressure storage offline
- Chiller offline
- H2 source offline
- POS offline

SOSS 3.0 UPGRADE

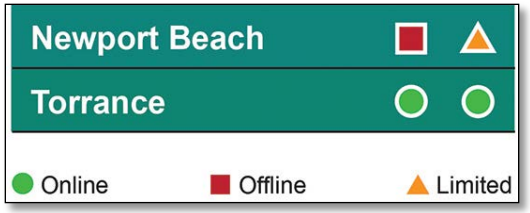
Improving user interface (Google map; mobile online)

Increasing data transmission interval from stations to once every 15 minutes at minimum

Improving quality of data

Increasing data sharing capabilities

Modifying the CaFCP station map



Implemented at Burbank (CA) station; to be implemented at 4 stations by June 2015, and 7 stations by December 2015.

ACCOMPLISHMENTS:
HySTEP (Hydrogen Station Equipment Performance) Device Designed

- ❑ Mobile--mounted on trailer
- ❑ Type IV 70 MPa tank(s) with at least a 4-7 kg capacity
- ❑ Designed to be able to perform subset of CSA HGV 4.3 tests
- ❑ SAE J2799 IrDA for communication tests and fills
- ❑ Tank and receptacle instrumented to monitor pressure ramp rate, ambient, tank, and gas conditions
- ❑ Leak simulation to check dispenser response

H2FIRST

Will test first CA hydrogen station in Sept. 2015

ACCOMPLISHMENTS

- ✓ Device design completed
- ✓ Go/No-go criteria met for device fabrication--device design reviewed by Project Team, DOE HQ, and Hydrogen Safety Panel and found acceptable

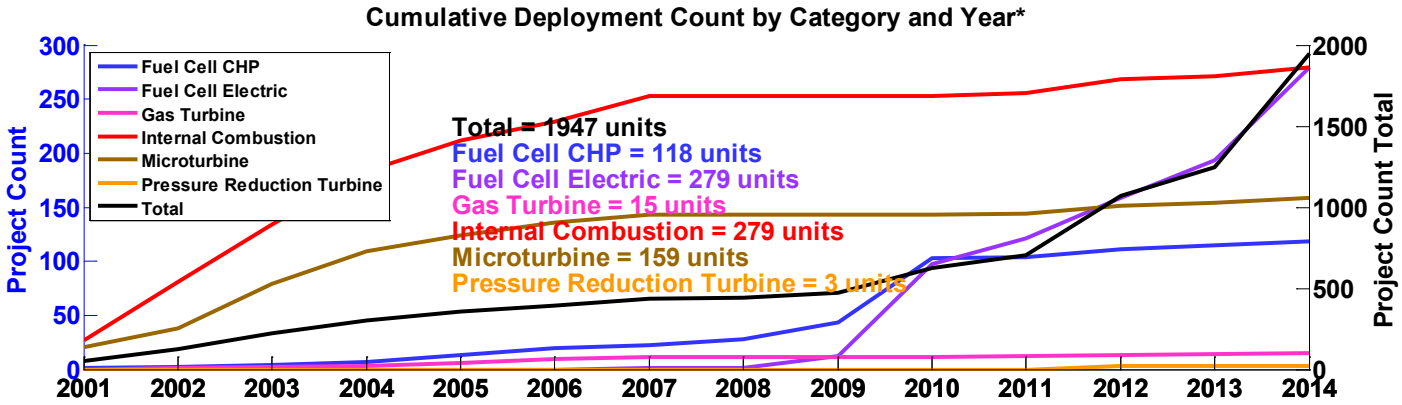
- ❖ **Co-designed by H2FIRST HySTEP Project Team**
- ❖ **Fabricated by Powertech Labs**

PARTNERS

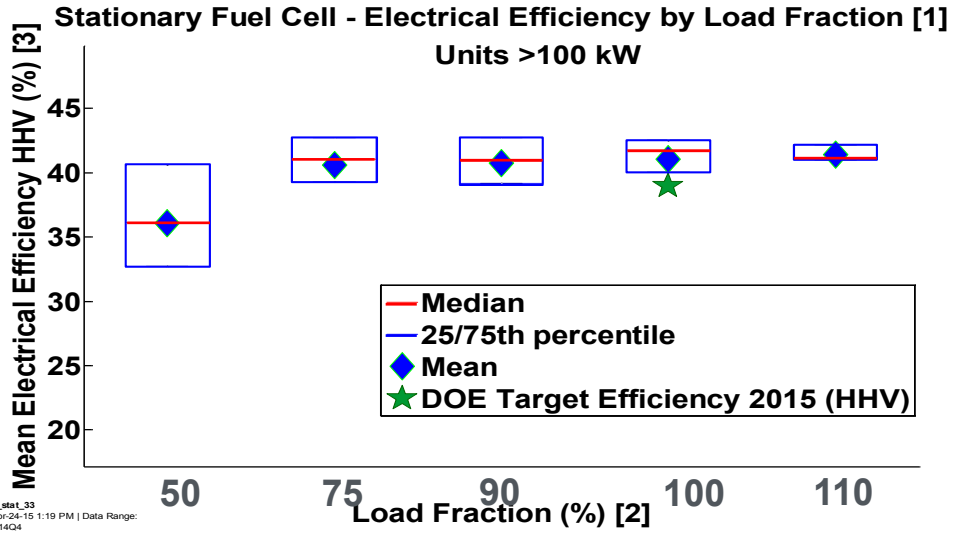
- Sandia National Labs
- National Renewable Energy Lab
- Air Liquide
- Boyd Hydrogen
- CA Air Resources Board
- Toyota
- PNNL H_2 Safety Panel

Developing and validating prototype device to measure hydrogen dispenser performance, to help accelerate commercial hydrogen station acceptance .

ACCOMPLISHMENTS: Stationary Fuel Cells



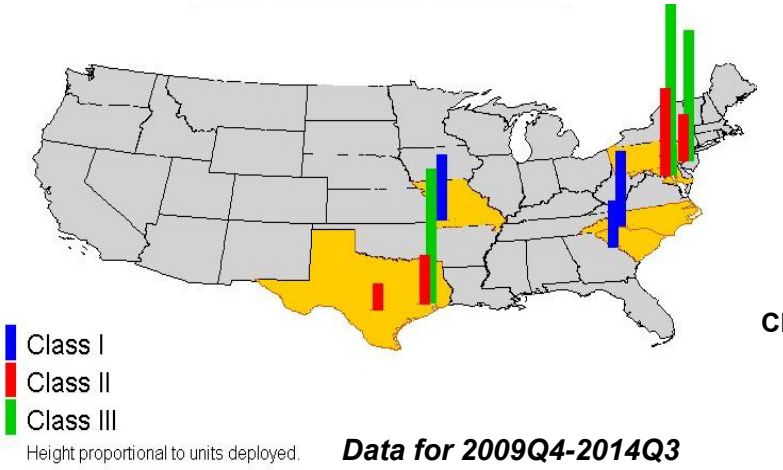
FC electric units deployed equal in number (279) to ICE units deployed.



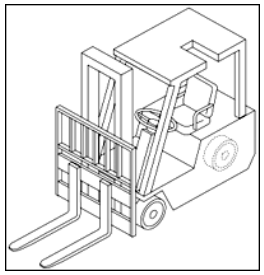
Beyond 75% load fraction, stationary FC mean efficiency exceeds 2015 DOE target.

In 2014, cumulative deployment of fuel cells match largest competitor, internal combustion engine, in number of installations.

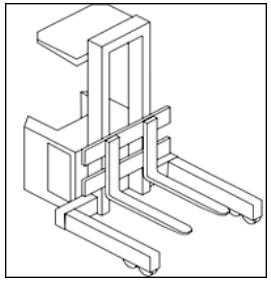
ACCOMPLISHMENTS: Fuel Cell Forklifts



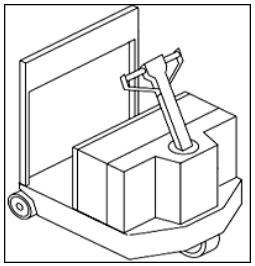
Data for 2009Q4-2014Q3



Class I: Electric Motor Rider Trucks

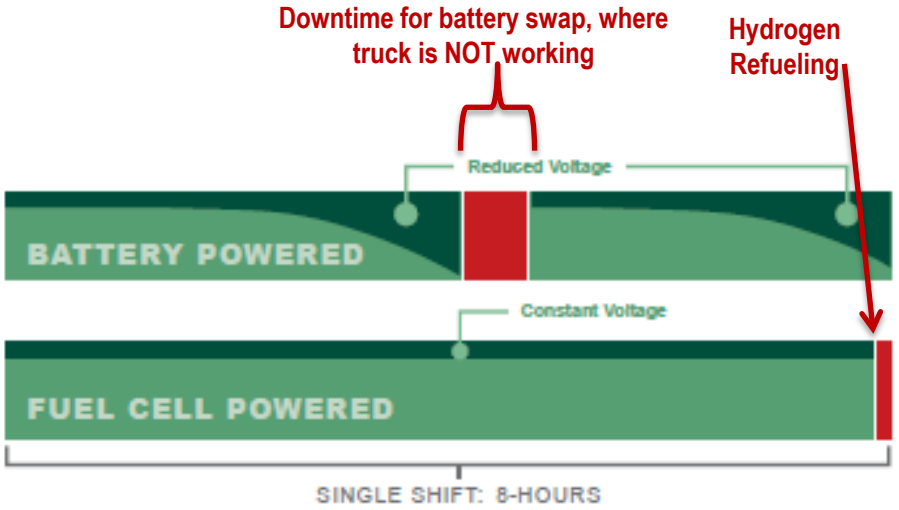


Class II: Electric Motor Narrow Aisle Trucks



Class III: Electric Motor Hand Trucks or Hand/Rider Trucks

- ✓ **720 units in operation:*** Expanding market, with success proven in real-world; customers deploying more without federal funding support
- ✓ **Avg. 2.5 min to fill and avg. 3.7 hrs operation between fills:** Shorter time for fueling means shorter downtime and more hours of operation, resulting in increased productivity and less revenue loss
- ✓ **Over 350,000 fills, with more than 280,000 kg of hydrogen dispensed:** More experience gained in the field and business case proven



* ***One project has completed. Only ARRA locations shown.***

Fuel cell forklift performance is being validated, based on real-world operation data from high-use facilities.

Grid Modernization

1. Devices and Integrated Systems Testing*
- ❑ Develop advanced storage systems, power electronics, other grid devices, and standards/test procedures
- ❑ Build capabilities; conduct device testing and validation
- ❑ Conduct multi-scale systems integration and testing

2. Sensing and Measurements
- ❑ Sensing for buildings, users, and T&D systems
- ❑ Data analytic and visualization techniques
- ❑ Unified grid-communications network

3. System Operations, Power Flow, and Control
- ❑ Architecture, system controls, enhanced power flow control device hardware
- ❑ Analytics and computation

4. Design and Planning Tools*
- ❑ Scale tools for comprehensive economic assessment
- ❑ Develop and adapt tools for improving reliance and reliability
- ❑ Build technologies and high-performance computing capabilities to speed-up analyses

5. Security and Resilience
- ❑ Identify/protect against threats and hazards and respond
- ❑ Recovery capacity time

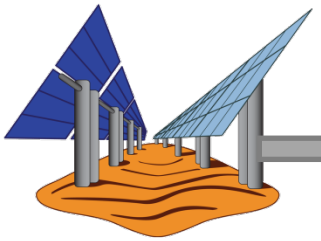
6. Institutional Support
- ❑ Support states, tribal governments, regional organizations
- ❑ Emerging technologies, valuation, markets, and future electric utility regulations

**** FCTO emphasis areas***

DOE grid modernization activities are ongoing--critical for enabling hydrogen energy storage.

Hydrogen Energy Storage/Grid Integration

Wind



Solar

Geothermal

Electricity Grid

Generator

Fuel Cell,
Internal Combustion,
Steam Turbine

Electrolyzer

Ramp–up &
Ramp-down
capability for
Grid stabilization

Natural Gas Infrastructure

Oxygen Storage

Hydrogen Storage

Value Added Applications

- Vehicle Fuel
- Fertilizer NH_3
- Emergency BuP FC

Hydrogen may be produced from a variety of renewable resources, and hydrogen-based energy storage could provide value to many applications and markets.

ACCOMPLISHMENTS: Electrolyzers Supporting the Grid

OBJECTIVE
Validate and demonstrate--to utilities and station owners--value of hydrogen fueling station electrolyzers to provide grid services.

Identify high-value locations to implement demand response (DR) and ancillary services using hydrogen stations.

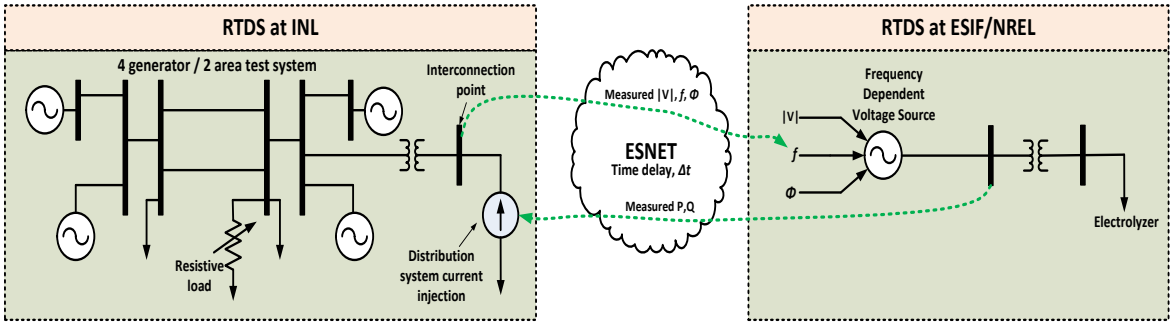
IMPACT
Present real and specific opportunities to both increase ability for grid to handle increasing penetration of variable renewable generation, while providing revenue that can decrease cost of hydrogen for transportation.

PARTNERS
- ❖ INL & NREL
- ❖ PG&E, CAISO, and one other CA utility (TBD)
- ❖ Humboldt State Univ., Florida State Univ.

FY15 FUNDING:
$3.66M ($2.1 INL; $1.56 NREL)

- ❑ Leverage real time digital simulator (RTDS) capabilities at INL
- ❑ Electrolyzer test bed at NREL for communication
- ❑ Model IEEE node feeder and electrolyzer in RTDS framework
- ❑ Validate electrolyzer model through power hardware-in-the-loop testing

- ❑ Investigate current DR programs to model dynamic conditions to identify best locations
- ❑ Model Bay-area grid opportunities using data from PG&E correlated with existing, planned (17 stations), and projected hydrogen infrastructure
- ❑ Explore DR aggregator partnerships
- ❑ Investigate novel DR programs, including wind, solar, and fuel cells
- ❑ Expand power system model (FY17) to include expansion of hydrogen infrastructure in Bay Area, LA Area, NE

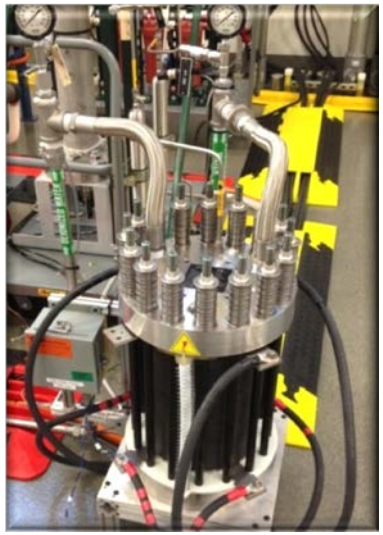


Initiated new project to perform dynamic modeling and validation of electrolyzers in real time grid simulation. Established real-time link between national labs (INL & NREL) to simulate electrolyzers on the grid.

ACCOMPLISHMENTS: "INTEGRATE"

Integrated Network Testbed for Energy Grid Research and Technology Experimentation

- ✓ **Completed design, installation and commissioning of 250 kW electrolyzer stack test bed**
  - ❑ AC/DC power supplies are capable of 500 kW
- ✓ **Successful data exchange from INL to NREL**
  - ❑ Bi-directional communication, allowing real-time exchange of data
- ✓ **First testing completed with Giner Inc.**
  - ❑ Performed FAT of three 150 kW PEM stacks, which were then shipped to customers in Europe
  - ❑ Working with Giner to prepare for testing of 1/3 MW and then 1 MW stacks requiring nearly 4000A DC
- ✓ **Currently operating 120 kW stack from Proton Onsite**

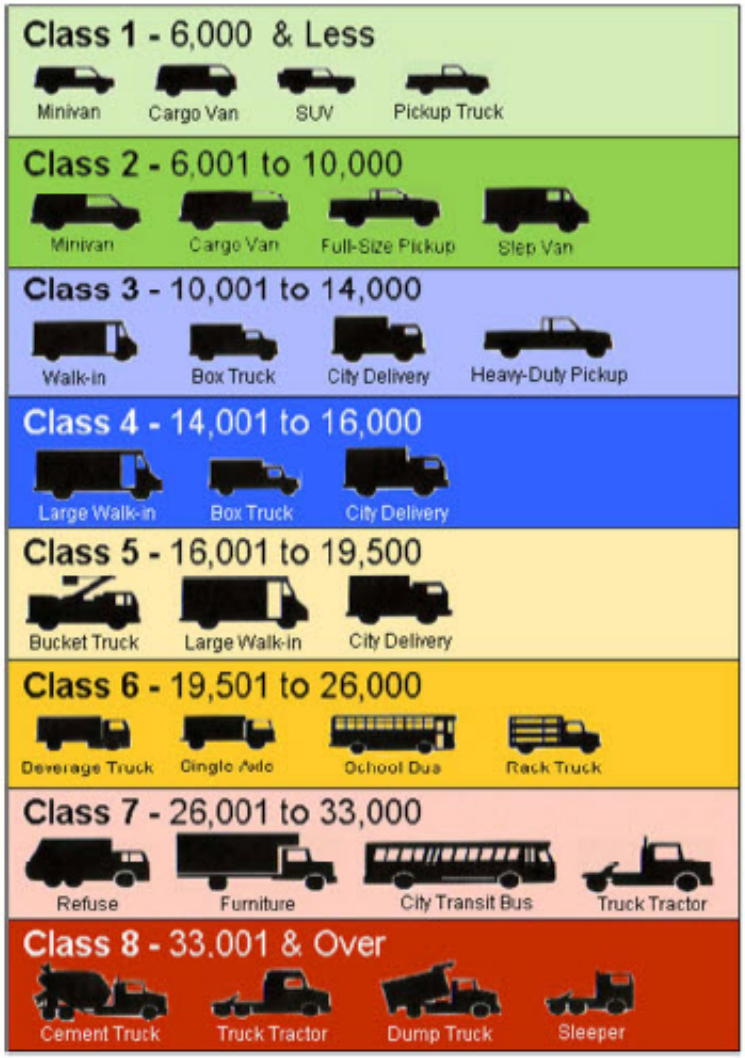


Designed, built, commissioned and operating electrolyzer stack test bed. Established first of its kind RTDS to RTDS communications network between NREL and INL. Developed data services to analyze and share data from test bed.

Developing Targets

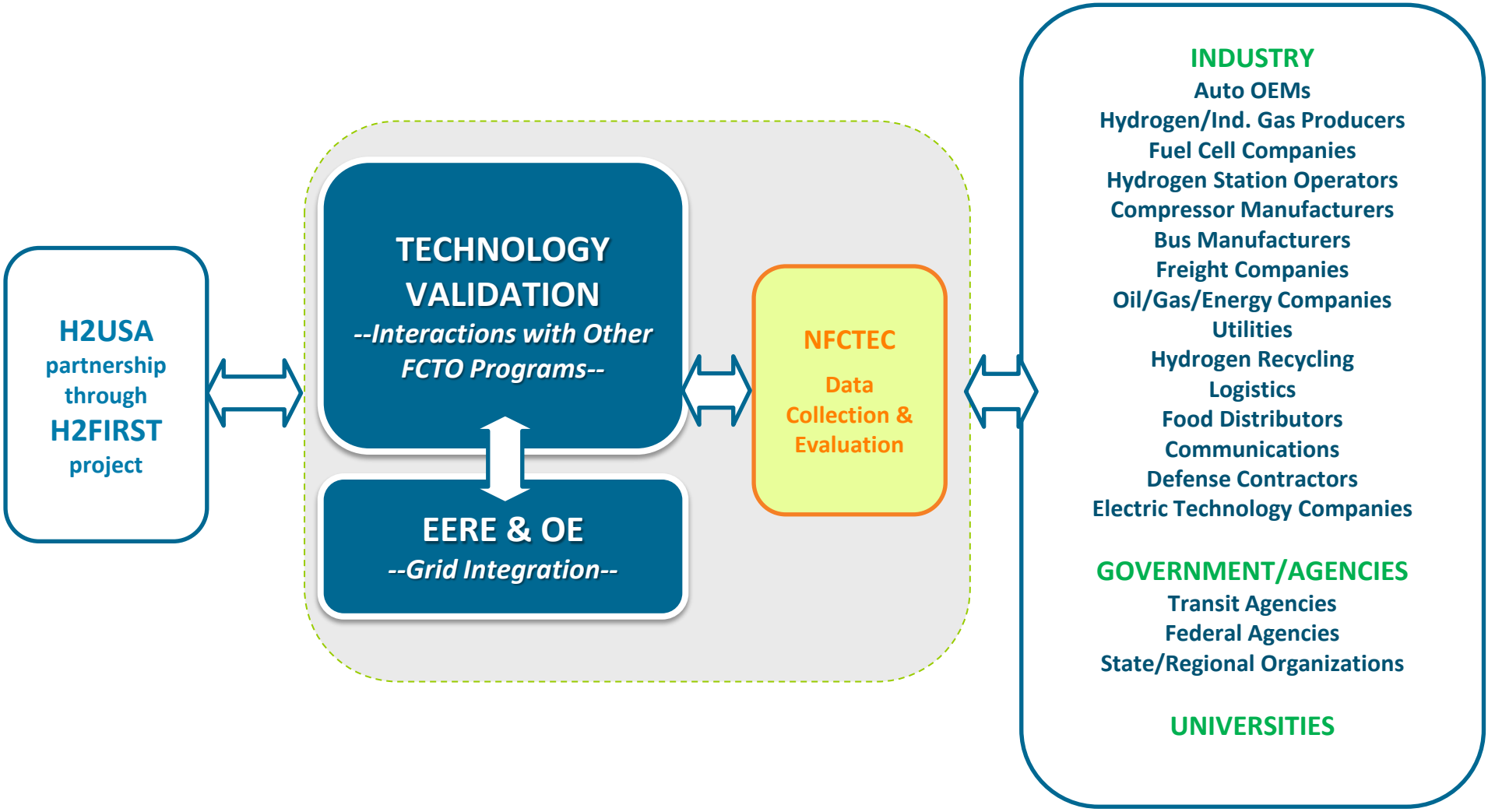
Request for Information planned:

- Appropriate truck classes and vocation for initial focus
  - ❑ Characterization of gross vehicle weight, range, drive cycle
- High-level vehicle targets and basis for each type of truck (e.g. mpg optimization)
- Assumptions
  - ❑ Battery power
  - ❑ Fuel cell power
  - ❑ Hydrogen storage
- System-level targets
  - ❑ Durability
  - ❑ Mass %



Targets are being developed for medium- and heavy-duty fuel cell trucks.

Collaborations



Activities are coordinated among various partners.

Funding Opportunity Announcements

DE-FOA-0001224 ***(closed 6/4/2015)***
Subtopic 2a: Design, Deployment, and Validation of Advanced, Low-cost Mobile Hydrogen Refuelers

Design, develop, deploy, and validate economically viable ***mobile hydrogen refuelers***.

- ❑ ***Phase 1 (Design and Development)…***minimize capital and operational costs while meeting performance metrics. Throughput 10 - 20 kg hydrogen every hour (from any tank condition; including dwell time), allowing for several back-to-back fills.
- ❑ ***Phase 2 (Demonstration and Validation)…***validate at minimum of 3 sites, for total of 18 months of retail operation

Grid Modernization Lab Call—FCTO Topics

Topic 1a: Building Manager Dispatch Tool for Integrated Fuel Cell/ Building/ Energy Storage

- ✓ Open source; for building managers
- ✓ Interface with building networks (e.g. Voltron)
- ✓ Communicate with grid for energy services/demand response

Topic 1b: Optimal Planning of Integrated Fuel Cell/ Building/ Energy Storage

- ✓ Open source; for microgrid designers
- ✓ Incorporate transactive grid interaction control capabilities
- ✓ Optimize simultaneously--component sizing and control parameters for building/equipment/environment/market

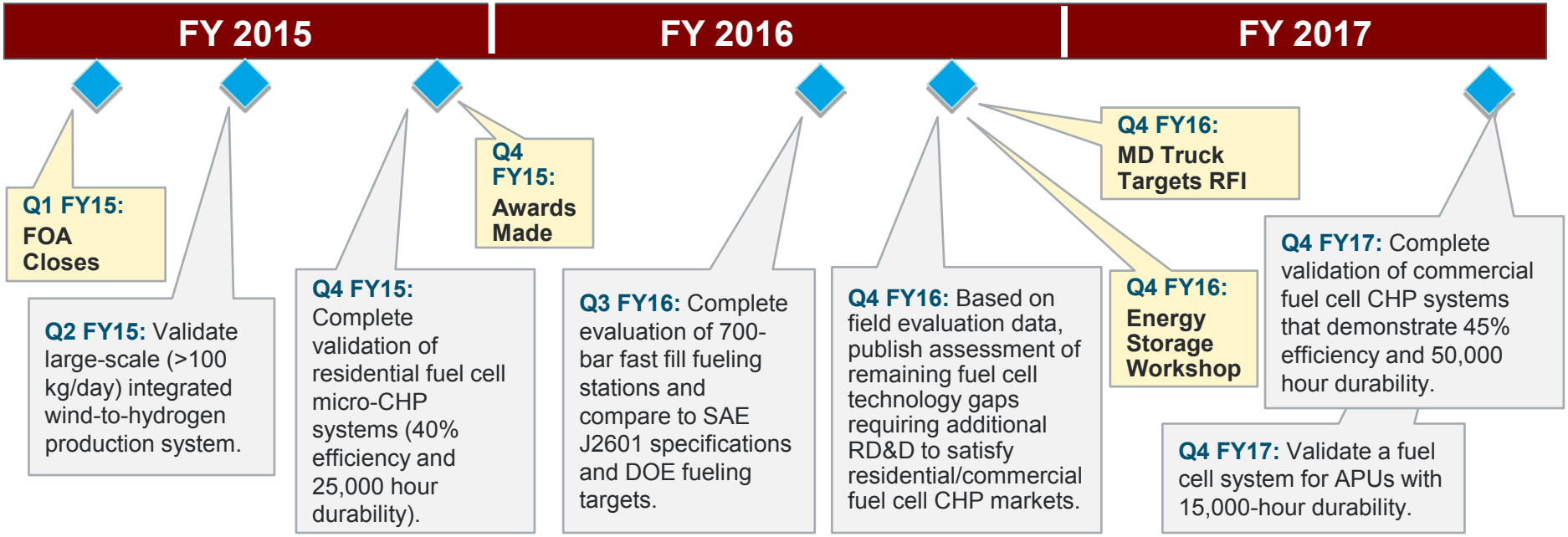
Topic 2: Capacity for Hydrogen Infrastructure and Fuel Cell Vehicles to Support the Grid

- ✓ FCEVs providing backup power to buildings—requirements; costs; benefits; increasing adoption of FCEVs
- ✓ Renewable hydrogen stations providing grid support
  - ❑ Hydrogen amount—for vehicle needs and grid services
  - ❑ Available capacity throughout day for grid services (driving/fueling behavior)
  - ❑ Sensitivity to increasing adoption of FCEVs

Mobile Refueler FOA & Grid Modernization Lab Call

Summary

- ✓ Fuel cell buses--several targets have been met or exceeded:
  - ❑ Top FCPP > 19,000 hrs, surpassing DOE/DOT target
  - ❑ MBRC surpasses 2016 target, approaching ultimate target
- ✓ Fuel cell vehicles--steady progress has been demonstrated over four evaluation periods with improvements especially in fuel cell durability, range, and fuel economy.
- ✓ Hydrogen stations--first commercially sold hydrogen in the U.S (CSULA).; new hydrogen stations coming online.
- ✓ Components—evaluating hydrogen compressors and cryogenic pressurized hydrogen storage and delivery.
- ✓ Supporting hydrogen infrastructure development—station performance testing and operational status notification.
- ✓ Developing new targets.
- ✓ Evaluating hydrogen based energy storage and the value of electrolyzers to provide grid services.



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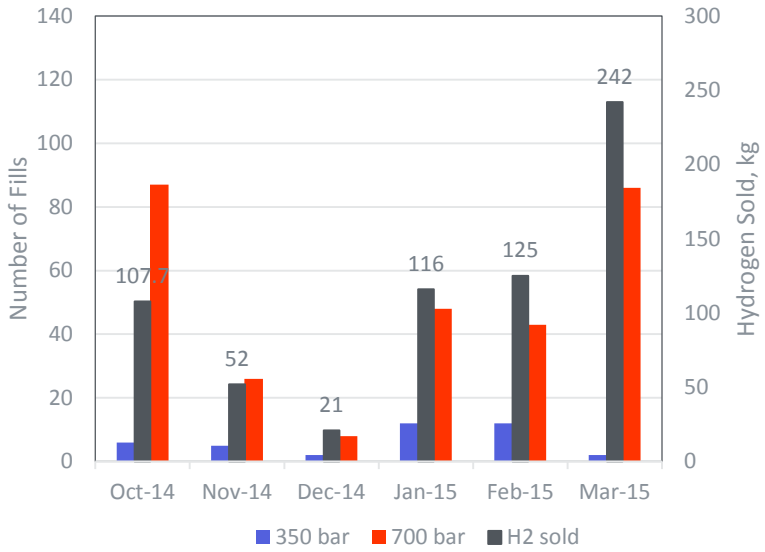
http://energy.gov/eere/fuelcells/fuel-cell-technologies-office

Backup Slides

ACCOMPLISHMENTS: Hydrogen Refueling at CSULA

- ✓ First in U.S. to receive seal of approval for sale of hydrogen on per kg basis as of January 2015
  - ❑ Testing was conducted in collaboration with the California Department of Weights and Measures, CAFCP and CARB
- ✓ Implemented installation of power and flow meters
- ✓ Installed buffer tanks
- ✓ Data continuously collected and analysis has been enabled



Station collecting data, analyzing performance. Plans in long term include smart grid, infrastructure, and expanded education opportunities.

ACCOMPLISHMENTS: Advanced High-pressure Electrolyzer

SunHydro #1

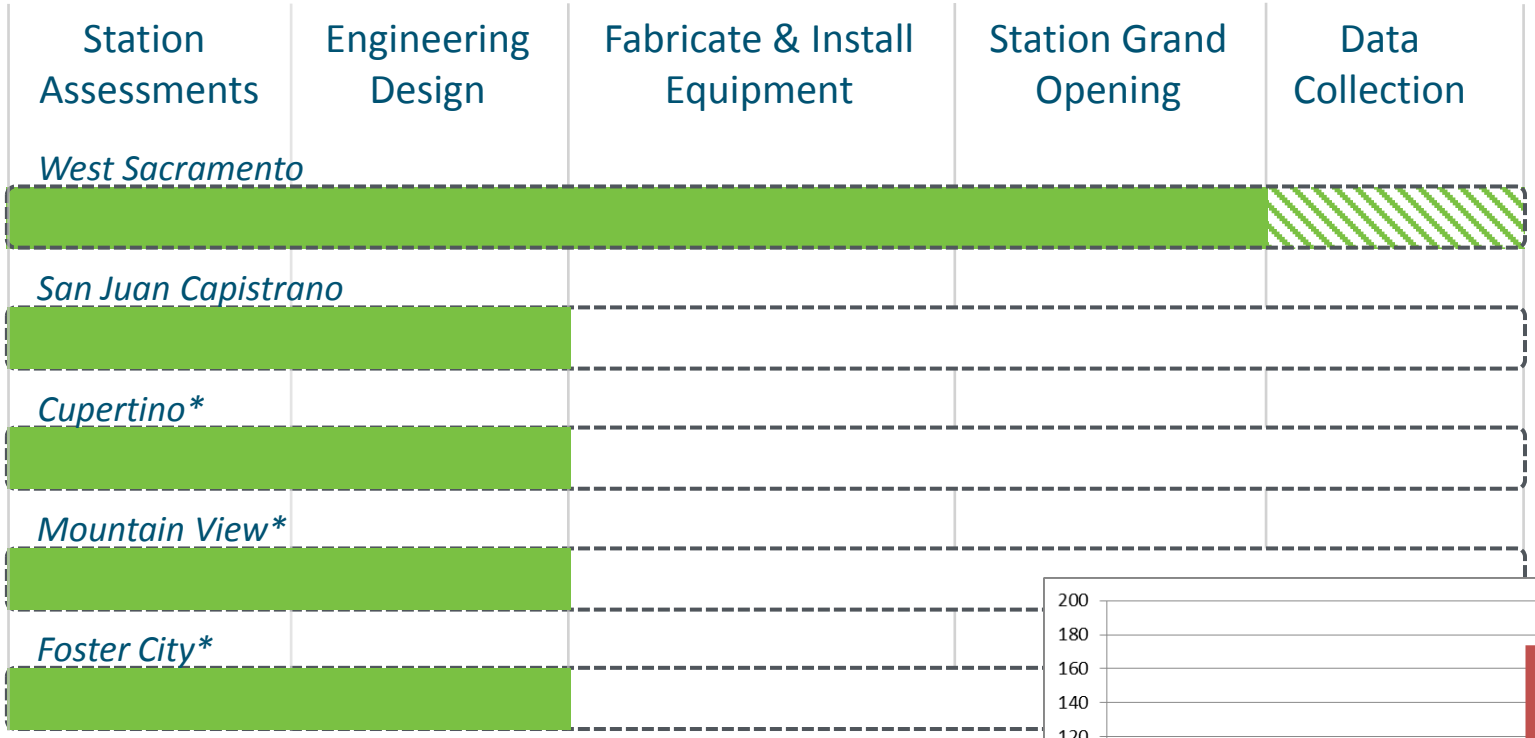
- ✓ 57 bar stack and system built and tested.
- ✓ Advanced storage received
- ✓ Data monitoring and energy measurements ongoing
  - ❑ Data reported to NREL for each quarter since 2013 Q4
  - ❑ 8 kWh/kg energy reduction

SunHydro #2

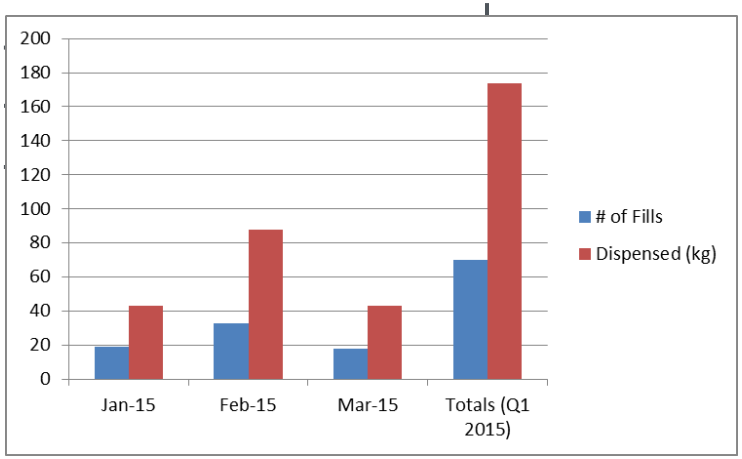
- ✓ Designed and fabrication well underway
- ✓ Advanced storage received
- ✓ Data acquisition hardware prepared

SunHydro#1 operating and performance data being collected. SunHydro#2 being fabricated.

ACCOMPLISHMENTS: Delivered Hydrogen Fueling Stations



***Planned Station – May be changed if other stations become available first.**

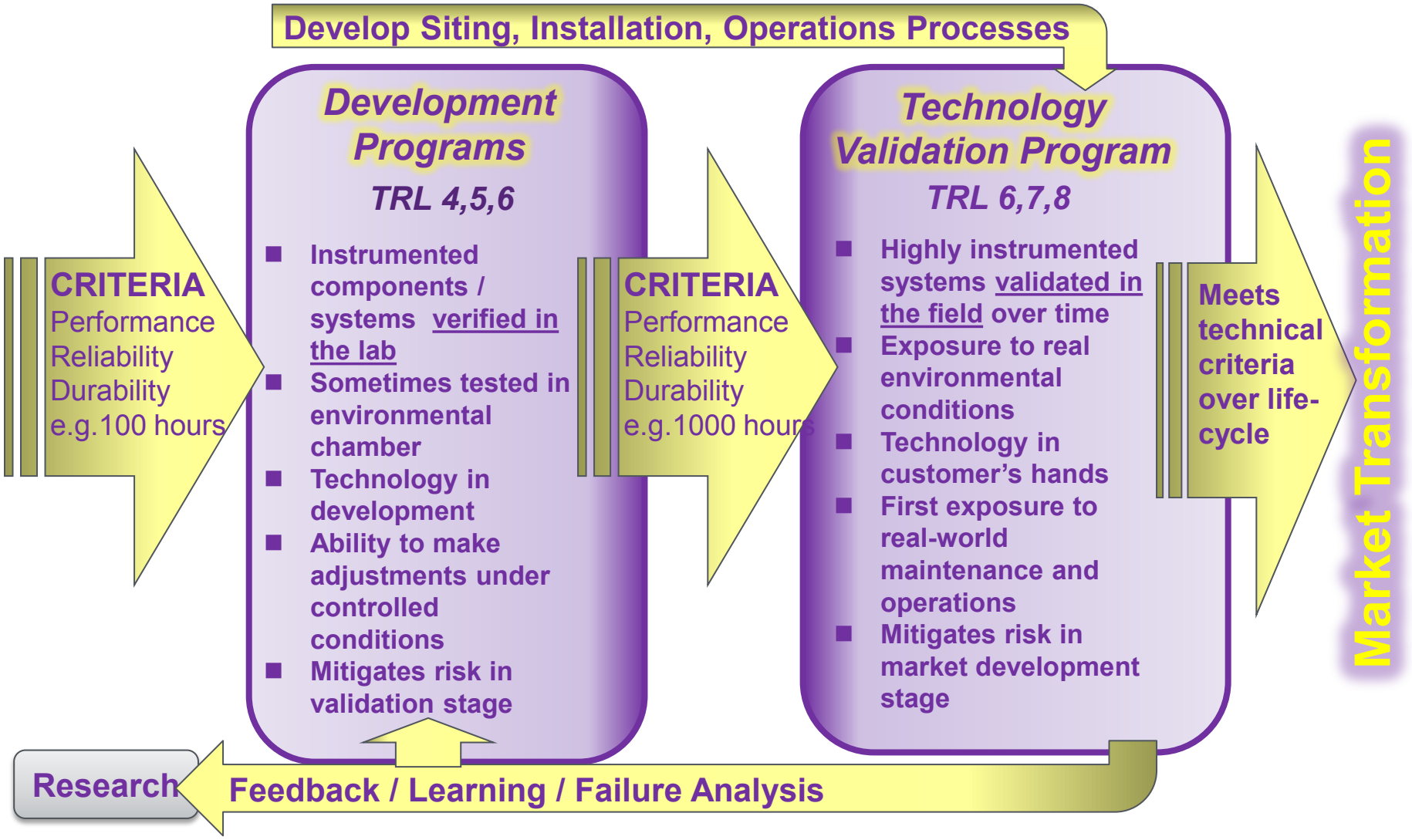


West Sacramento site:

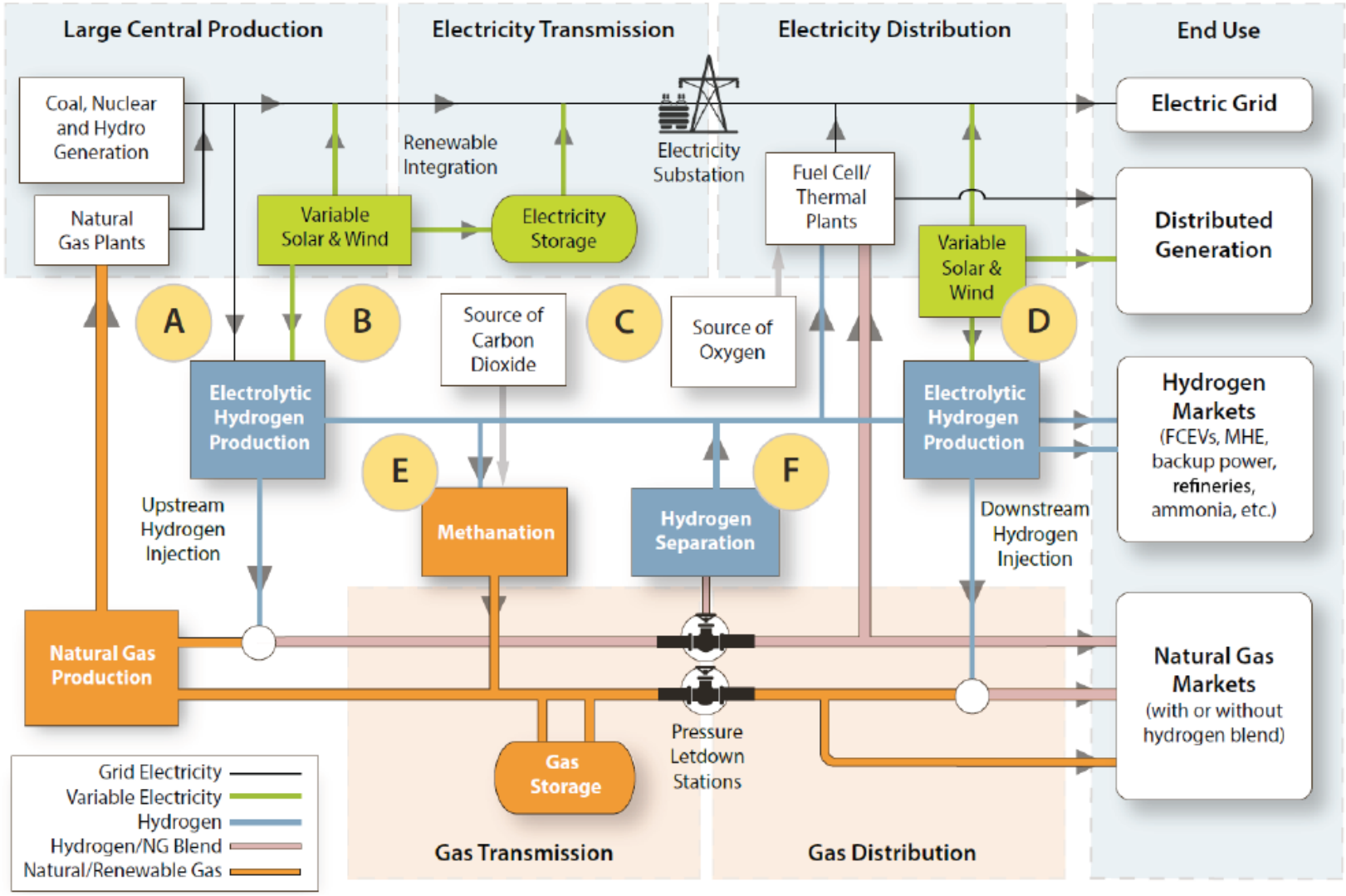
- ✓ Data collection has begun.
- ✓ ~170 kg of H_2 dispensed in 2015Q1.

900 bar ionic compression technology being tested and validated.

Strategy


Develop Siting, Installation, Operations Processes
CRITERIA
Performance
Reliability
Durability
e.g.100 hours
Development Programs
TRL 4,5,6
Instrumented components / systems verified in the lab
Sometimes tested in environmental chamber
Technology in development
Ability to make adjustments under controlled conditions
Mitigates risk in validation stage
CRITERIA
Performance
Reliability
Durability
e.g.1000 hours
Technology Validation Program
TRL 6,7,8
Highly instrumented systems validated in the field over time
Exposure to real environmental conditions
Technology in customer's hands
First exposure to real-world maintenance and operations
Mitigates risk in market development stage
Meets technical criteria over life-cycle
Market Transformation
Research
Feedback / Learning / Failure Analysis

Hydrogen Energy Storage Pathways



A. Electrolysis for Grid Support

B. Integration of large-scale central renewables

C. Conversion to grid electricity

D. Distributed production for variable resources

E. Methanation for renewable gas synthesis

F. Hydrogen Separation

Source: http://www.nrel.gov/docs/fy15osti/62518.pdf