Technology Validation Program Area

-Plenary Presentation-

Jim Alkire
Fuel Cell Technologies Office

2017 Annual Merit Review and Peer Evaluation Meeting
June 5 - 9, 2017
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 H₂/day (at 5kg H₂/ 3 min; 700 bar)

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:** Develop processes and systems to move technology from labs into the field, through independent data collection/analysis and real-world demonstrations.
TECHNOLOGY VALIDATION develops processes and systems to move technology from labs into the field, through independent data collection/analysis and real-world demos.

**STRATEGY**
- VERIFY components in lab
- INTEGRATE components into systems
- VALIDATE performance against targets under real-world conditions
- DEVELOP siting, construction, installation, and operations processes
- SUPPORT business practices, facilities, or services
- PROVIDE feedback to R&D and target setting

**IMPACT**
- PROVIDE unbiased and independent information to investors and decision-makers
- EVALUATE technology market readiness
- MITIGATE technical risks for market introduction

**BARRIERS**
- Lack of FCEV and FCEB performance and durability data
- Lack of hydrogen refueling infrastructure performance and availability data
- Hydrogen from renewable resources
EMPHASIS ON R&D FEEDBACK

VEHICLES
- Light-duty cars, buses, delivery trucks

INFRASTRUCTURE / H2FIRST
- Fueling station and component performance and reliability
- Delivery and dispensing
- Meter benchmarking
- Fuel contaminant detection
- Mobile refueler

GRID INTEGRATION / ENERGY STORAGE
- Electrolyzers in real-time grid simulation
- Energy Dispatch Controller
- Hydrogen-vehicle-grid systems
- High current density SOEC system

H2@Scale
- Analysis and data collection
- Electrolyzer MEA
- Dynamic Compressor Operation
- High-temp electrolysis testing
- Planned CRADA call

FY 2017 Appropriation = $18M

Technology Validation Budget

<table>
<thead>
<tr>
<th>Category</th>
<th>Budget (Millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VEHICLES</td>
<td></td>
</tr>
<tr>
<td>Light-duty cars, buses</td>
<td>2.00</td>
</tr>
<tr>
<td>Delivery trucks</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td>9.00</td>
</tr>
<tr>
<td>INFRASTRUCTURE / H2FIRST</td>
<td></td>
</tr>
<tr>
<td>Fueling station</td>
<td>5.00</td>
</tr>
<tr>
<td>Component performance</td>
<td>5.00</td>
</tr>
<tr>
<td>and reliability</td>
<td></td>
</tr>
<tr>
<td>Delivery</td>
<td></td>
</tr>
<tr>
<td>dispensing</td>
<td></td>
</tr>
<tr>
<td>Meter benchmarking</td>
<td></td>
</tr>
<tr>
<td>Fuel contaminant detection</td>
<td></td>
</tr>
<tr>
<td>Mobile refueler</td>
<td></td>
</tr>
<tr>
<td>GRID INTEGRATION / ENERGY STORAGE</td>
<td></td>
</tr>
<tr>
<td>Electrolyzers</td>
<td>2.00</td>
</tr>
<tr>
<td>in real-time</td>
<td></td>
</tr>
<tr>
<td>grid simulation</td>
<td></td>
</tr>
<tr>
<td>Energy Dispatch</td>
<td>2.00</td>
</tr>
<tr>
<td>Controller</td>
<td></td>
</tr>
<tr>
<td>Hydrogen-vehicle</td>
<td>2.00</td>
</tr>
<tr>
<td>grid systems</td>
<td></td>
</tr>
<tr>
<td>High current density</td>
<td>9.00</td>
</tr>
<tr>
<td>SOEC system</td>
<td></td>
</tr>
<tr>
<td>H2@Scale</td>
<td></td>
</tr>
<tr>
<td>Analysis</td>
<td>2.00</td>
</tr>
<tr>
<td>and data collection</td>
<td></td>
</tr>
<tr>
<td>Electrolyzer MEA</td>
<td></td>
</tr>
<tr>
<td>Dynamic Compressor</td>
<td></td>
</tr>
<tr>
<td>Operation</td>
<td></td>
</tr>
<tr>
<td>High-temp electrolysis</td>
<td></td>
</tr>
<tr>
<td>testing</td>
<td></td>
</tr>
<tr>
<td>Planned CRADA</td>
<td></td>
</tr>
<tr>
<td>call</td>
<td></td>
</tr>
</tbody>
</table>
Project Portfolio

LAB TESTING

- HyStEP device (station perf.)
- cryo-H₂ storage & LH₂ pump
- H₂ meter benchmark testing
- component performance evaluation
- hydrogen contamination evaluation
- fuel cell

DEVELOPMENT

- H₂ high-P tube trailer
- mobile H₂ refueling
- hybrid electric FC parcel truck

DEMO & VALIDATION

- AC Transit, Oakland, CA
- Hyundai
- Mercedes
- GM
- Nissan
- Toyota
- Honda

- SunLine, Thousand Palms, CA
- OCTA, Orange County, CA
- UCI Irvine, CA

grid simulation & resiliency (RTDS)
energy dispatch controller
ACCOMPLISHMENTS: Hydrogen Stations & Fuel Cell-based Transportation Data Collection and Analysis

Real-world performance of technologies are validated in field through data collection and analysis.

**KEY ACCOMPLISHMENTS**

**Stations:**
- >3x number of stations providing data
- >10x H₂ dispensed vs. last year
- Dispensers leading cause of downtime; overtaking compressors as #1; failure rates improving as more hydrogen dispensed

**Cars:**
- 2 fuel cell stacks now over 5,000 hours
- 227 cars traveled >7 million miles--to date (42 vehicles and 2.4 million miles--latest evaluation period)

**Buses:**
- One FCEB >23,000 hours now; 6 buses >18,000 hours (2016 DOE/DOT target)
- Fleet max values exceeding ultimate targets

**WHY?**
Validate car, bus, hydrogen station performance through analysis of real-world performance data for current status, benchmarking, and technology readiness.

**BUSES**
*Fuel cell buses exceeding targets...*

<table>
<thead>
<tr>
<th></th>
<th>Fleet Avg.</th>
<th>Fleet Max</th>
<th>2016 Target</th>
<th>Ult. Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability</td>
<td>----</td>
<td>93%</td>
<td>85%</td>
<td>90%</td>
</tr>
<tr>
<td>Durability</td>
<td>----</td>
<td>23,423 hrs</td>
<td>18,000 hrs</td>
<td>25,000 hrs</td>
</tr>
<tr>
<td>Fuel Econ.</td>
<td>----</td>
<td>7.22 mpgge</td>
<td>8 mpgge</td>
<td>8 mpgge</td>
</tr>
<tr>
<td>Miles betw.</td>
<td>4,710/20,705</td>
<td>3,500/15,000</td>
<td>4,000/20,000</td>
<td></td>
</tr>
<tr>
<td>Road Calls</td>
<td>(bus/FC system)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**CARS**

<table>
<thead>
<tr>
<th></th>
<th>200 - 300 mi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td></td>
</tr>
<tr>
<td>Durability</td>
<td>4,100 hrs (max fleet avg.)</td>
</tr>
<tr>
<td>Fuel Econ.</td>
<td>51 mpgge (avg. on-road)</td>
</tr>
<tr>
<td>Fuel Econ.</td>
<td>up to 68 mpgge (commercial vehicles)</td>
</tr>
<tr>
<td>Fuel Cell Eff.</td>
<td>57% (avg. at ½ power)</td>
</tr>
</tbody>
</table>

**H₂ STATIONS**
*Validating emerging H₂ infrastructure*

- H₂ Dispensed* 202,364 kg
- Avg. Fill Time 4.6 min
- # of Stations 61 (current) 36 (planned)

*Cumulative through Q4, 2016

Lead: NREL

TV001, 008, 017
ACCOMPLISHMENTS: H₂ Meter Benchmarking Testing

Testing accuracy of flow meters for commercial sale of hydrogen is providing feedback to flow meter manufacturers, helping develop improved flow meter technologies.

WHY?
- H₂ meters currently meeting 5% tolerance level in the field
- All relaxed accuracy classes will sunset in 2020

KEY ACCOMPLISHMENTS
- Designed/built lab-grade gravimetric hydrogen standard
- Conducted high-pressure testing of commercially available flow meters (2 Coriolis; 1 Turbine) over range of simulated SAE J2601 fueling protocols

<table>
<thead>
<tr>
<th>Accuracy Class</th>
<th>Application or Commodity Being Measured</th>
<th>Acceptance Tolerance</th>
<th>Maintenance Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>Hydrogen gas as a vehicle fuel</td>
<td>1.5%</td>
<td>2.0%</td>
</tr>
<tr>
<td>3.0</td>
<td>Hydrogen gas as a vehicle fuel</td>
<td>2.0%</td>
<td>3.0%</td>
</tr>
<tr>
<td>5.0</td>
<td>Hydrogen gas as a vehicle fuel</td>
<td>4.0%</td>
<td>5.0%</td>
</tr>
<tr>
<td>10.0</td>
<td>Hydrogen gas as a vehicle fuel</td>
<td>5.0%</td>
<td>10.0%</td>
</tr>
</tbody>
</table>

*Acceptance tolerance = first test in lab
**Maintenance tolerance = test in field

Table T.2. Accuracy Classes and Tolerances for Hydrogen Gas-Measuring Devices

<table>
<thead>
<tr>
<th>Tolerance Levels</th>
<th>All Cases</th>
<th>High Flow</th>
<th>Typical Ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>2%</td>
<td>82.2%</td>
<td>64.6%</td>
<td>88.1%</td>
</tr>
<tr>
<td>5%</td>
<td>99.9%</td>
<td>98.8%</td>
<td>100%</td>
</tr>
<tr>
<td>10%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

BEST METER PROBABILITY THAT SINGLE FILL WILL BE WITHIN % TOLERANCE LEVELS

Lead: NREL
Partnering with NIST

TV037
ACCOMPLISHMENTS:
Hydrogen Station and Components Evaluation

Tube cutting and cleaning processes shown to have substantial contamination effects.

WHY?
Determining contaminants and methods to remove contaminants helps identify opportunities to improve station reliability.

KEY ACCOMPLISHMENTS

Contaminant Detection
✓ Determined *greases* containing siloxanes harmful to fuel cells
✓ Determined effect of *tube-cutting* and *cleaning techniques* on particulate contamination (metal particles)
✓ Quantified effect of tube cleaning techniques on reducing metal particulates--plugging with tube brush doesn’t require significant additional effort, yet it can reduce metal particulates

Reliability & Maintenance
✓ Showed 1/3 of maintenance hours at stations are for compressors
✓ Communicating results with equipment manufacturers
ACCOMPLISHMENTS:
Hydrogen Station and Components Evaluation

Energy use of various station components quantified; areas for further improvement identified.

WHY?
Benchmarking station component energy use helps identify components to focus on to achieve better efficiencies and reduce costs.

KEY ACCOMPLISHMENTS

Power & Energy Demand
✓ Quantified energy consumption of major station components and impact on station operation costs
✓ Chiller performance shown to be highly dependent on ambient temperature and station throughput, ranging from <1 kWh/kg to 7 kWh/kg
✓ Compressor performance found to be constant around 4-6 kWh/kg

Lead: NREL
Partners: PDC; PPI/Sundyne; Shell Hydrogen; CSULA; SCAQMD; Sunline; H2Frontiers; Proton OnSite; FirstElement
ACCOMPLISHMENTS: Developing & Demonstrating Cryo-H₂ Storage & Liquid-H₂ Pump

Demonstrated performance characteristics and benefits of liquid hydrogen pump through testing over multiple cycles.

WHY?
Potential to increase hydrogen storage density (and vehicle driving range) by 30% while enabling 5 minute refuels and minimizing delivery cost.

KEY ACCOMPLISHMENTS
✓ Collected LH₂ pump performance and durability data over 456 cycles and 1,650 kg H₂
✓ Demonstrated 1.55 kgH₂/min (93 kgH₂/h) average pumping rate
✓ Demonstrated low consumption of electricity (1.1 kWh/kgH₂ active; .5 kVAh/kgH₂ apparent)
✓ Estimated 3.6% venting losses in a future LH₂ pump station with improved design

Lead: LLNL
Partners: Linde N. America; BMW; Spencer Composites
Design completed for fully functional hydrogen fueling station on wheels; ready to begin construction.

**WHY?**
- Self-contained, 700-bar capable, J2601-compliant
- Short-term coverage while stations built
- Temporary backup while stations down

**SPECIFICATION** | **DESCRIPTION**
--- | ---
Pressure Class | H70 (70 MPa) after compressing high bank storage
Pre-cooling | T30 (-30°C) or T40 (-40°C)
Performance | Up to 15 kg per hour, 100-120 kg in 8-10 hours
Fueling Protocol | SAE J2601-2014 table based for 2-7 kg tanks. SAE J2799-2014
Setup | One hour for limited performance, 8 hours for full performance
Storage | Up to 170 kg H2 at 45 MPa with ability to connect to external storage
Power | On-board 480VAC, low noise, low emissions diesel generator with option of using external power
Usage | Dispenser human machine interface allows fueling by minimally trained users.

**KEY ACCOMPLISHMENTS**
- Completed specifications
- Completed detailed design
- Completed hazard analysis
- Ordered long lead-time equipment

**Lead:** Electricore  
**Partners:** Air Liquide; HTEC; Quang Assoc.; Manta Consulting
ACCOMPLISHMENTS: Developing & Demonstrating Hybrid Electric Fuel Cell Parcel Truck

Hybrid electric fuel cell parcel truck designed, built, and on track for 2017 demonstration.

**WHY?**
- Extend range from 75 to 125 miles
- Validate in real-world operation (up to 16 vans)
- Potential to replace ~46,000 diesel walk-in vans in UPS' fleet

**KEY ACCOMPLISHMENTS**
- Completed detailed design
- Completed hazard analysis
- Integrated powertrain components and hydrogen fuel system onto chassis

**Lead:** Center for Transportation & the Environment (CTE)

**Partners:** University of Texas; Unique Electric Solutions; Hydrogenics USA; Valence Technology; UPS
ACCOMPLISHMENTS:
Fuel Cell Electric Trucks (FCET) Target Development

Demonstrated feasibility of FCETs for many applications; establishing techno-economic targets.

- Analysis and Publications
- Draft Targets
- Stakeholder Feedback

Representative Truck Market Data Sets

H₂ Storage Volumes
Body Builder Guides and Specs

H₂ Storage System Mass
Developed Physical Model

Component Sizing and Simulation
Autonomie Software

<table>
<thead>
<tr>
<th>Representative Vehicle Class and Vocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 2 Van</td>
</tr>
<tr>
<td>Class 3 Enclosed Van</td>
</tr>
<tr>
<td>Class 3 School Bus</td>
</tr>
<tr>
<td>Class 3 Service</td>
</tr>
<tr>
<td>Class 4 Delivery Van</td>
</tr>
<tr>
<td>Class 5 Utility</td>
</tr>
<tr>
<td>Class 6 Construction</td>
</tr>
<tr>
<td>Class 7 School Bus</td>
</tr>
<tr>
<td>Class 8 Construction</td>
</tr>
<tr>
<td>Class 8 Linehaul</td>
</tr>
<tr>
<td>Class 8 Refuse</td>
</tr>
<tr>
<td>Class 8 Tractor Trailer</td>
</tr>
</tbody>
</table>

Lead: Argonne National Lab
Partners: DOE Fuel Cell Technologies Office; NREL
ACCOMPLISHMENTS:
Integrating H₂ & Fuel Cells with the Grid

Created open-source tool (Energy Dispatch Controller) to foster growth in fuel cell-integrated buildings with emphasis on optimal dispatch control.

WHY?
- Optimized dispatch for buildings with integrated components – fuel cell, HVAC, boiler, thermal and electrical storage systems
- Participation of buildings and components in ancillary grid services
- Enabling better planning—optimum component selection and sizing (onsite generation/storage, etc.)

KEY ACCOMPLISHMENTS:
- Energy Dispatch Controller--initial formulation of algorithms and forecasting
- Functional GUI interface
- Building design module
- Co-simulation environment

Lead: NREL
Partners: PNNL; NREL; Washington State Univ.; Humboldt Univ.; Doosan; Plug Power; Ballard
ACCOMPLISHMENTS: Integrated Systems Modeling of H₂-Vehicle-Grid Interactions

Technical potential for centralized electrolysis to provide grid peak shaving and valley filling support for California in 2025 has been modeled for first time.

WHY?
Optimize operation and capacity of electrolyzer and hydrogen storage at renewable hydrogen stations for:
- Demand response
- Vehicle fuel
- Absorbing lower-cost curtailed renewable power

KEY ACCOMPLISHMENTS
- Developed sub-models (individual vehicle; dynamic station; FCEV adoption and H₂ station deployment)
- Integrated sub-models with hydrogen station models developed by NREL
- Performed preliminary case studies

Lead: LBNL
Partners: NREL, INL
ACCOMPLISHMENTS: Electrolyzers in Real Time Grid Simulation

Connected real-time grid simulator at INL with electrolyzer testbed at NREL to test capabilities to absorb curtailed renewable energy.

WHY?
Demonstrate fast-reacting performance of electrolyzers; characterize potential and highest economic value of their installation to enable their participation in energy markets and demand response programs.

KEY ACCOMPLISHMENTS
✓ Completed first of a kind, distributed real-time simulation with PHIL (electrolyzer) between INL and NREL; 200 hours (FY 2016) and 300 hours (FY 2017) of testing
✓ Ensured that electrolyzer stack efficiency and hydrogen quality is acceptable

Partners: NREL, INL
ACCOMPLISHMENTS: H2@Scale

Improving fidelity of H2@Scale value proposition through detailed analyses of market potential, resources, emissions, economic factors, and regional opportunities and challenges.

WHY?
Potential for wide-scale hydrogen production and utilization in U.S. that will improve stability of electric grid and economics of baseload power generation, while economically producing hydrogen that can be distributed and used in industrial and transportation applications.

KEY ACCOMPLISHMENTS:
Through initial analysis, determined that:

- Hydrogen demand of 60 MMT/yr possible when transportation and industry are considered
- Resources available to meet that demand
- Using renewable resources would reduce emissions and fossil use by >15%

* For the U.S., by the year 2040.

Lead: NREL
Partners: ANL, LBNL, PNNL, INL, LLNL, DOE Nuclear Energy Office
ACCOMPLISHMENTS:
High-temperature Electrolysis (HTE) Test Stand

Established technical and functional requirements for integrated nuclear-renewable-HTE test bed and developed dynamic nuclear-HTE process model.

WHY?
- Exploits thermal energy sources with higher thermodynamic efficiency
- Provides flexible operation of nuclear power plants as load-following plants that switch to hydrogen production based on market signals
- Provides large-scale energy storage based on diurnal and seasonal electricity demand

KEY ACCOMPLISHMENTS
Establishing an integrated nuclear-renewable-HTE test bed (DETAIL)
- Engineering design ongoing
- Renewable micro-grid in place
- Nuclear reactor emulator and thermal loop under construction
- HTE test skid work plan completed

Dynamic process model for renewable-nuclear-HTE coupling developed and will be validated

Lead: INL
Partners: DOE Nuclear Energy Office, EPRI, utilities, SOEC manufacturers, H₂ suppliers, syngas consumers
Activities are coordinated among various partners.
Summary

VEHICLES

- Fuel cell delivery truck designed, built, and on track for 2017 demonstration
- MD/HD truck targets—demonstrated feasibility for many applications; establishing techno-economic targets
- Fuel cell bus durability is >23,000 hrs; several LDV fuel cell stacks now over 5,600 hours

GRID INTEGRATION/ENERGY STORAGE

- Modeled technical potential for centralized electrolysis to provide grid peak shaving and valley filling support
- Created open-source tool to foster growth in fuel cell-integrated buildings with emphasis on optimal dispatch control
- Connected real-time grid simulator at INL with electrolyzer testbed at NREL to test capabilities to absorb curtailed renewable energy

INFRASTRUCTURE & H2@Scale

- Testing accuracy and providing feedback to H₂ flow meter manufacturers
- Tube cutting and cleaning processes shown to have substantial contamination effects at H₂ stations
- Demonstrated performance characteristics and benefits of liquid hydrogen pump
- Design completed for fully functional hydrogen fueling station on wheels; ready to begin construction
- Improving fidelity of H2@Scale value proposition through detailed analyses
## Contacts

<table>
<thead>
<tr>
<th>Name</th>
<th>Role</th>
<th>Office Location</th>
<th>Phone Number</th>
<th>Email</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jason Marcinkoski</td>
<td>Team Lead</td>
<td></td>
<td>202-586-7466</td>
<td><a href="mailto:Jason.Marcinkoski@ee.doe.gov">Jason.Marcinkoski@ee.doe.gov</a></td>
</tr>
<tr>
<td>Jim Alkire</td>
<td>Golden Office</td>
<td></td>
<td>720-356-1426</td>
<td><a href="mailto:James.Alkire@ee.doe.gov">James.Alkire@ee.doe.gov</a></td>
</tr>
<tr>
<td>Shaun Onorato</td>
<td>Contractor Support</td>
<td></td>
<td>720-356-1309</td>
<td><a href="mailto:Shaun.Onorato@ee.doe.gov">Shaun.Onorato@ee.doe.gov</a></td>
</tr>
<tr>
<td>Elvin Yuzugullu</td>
<td>Contractor Support</td>
<td></td>
<td>202-586-9583</td>
<td><a href="mailto:Elvin.Yuzugullu@ee.doe.gov">Elvin.Yuzugullu@ee.doe.gov</a></td>
</tr>
<tr>
<td>James Kast</td>
<td>Fellow</td>
<td></td>
<td>202-586-8477</td>
<td><a href="mailto:James.Kast@ee.doe.gov">James.Kast@ee.doe.gov</a></td>
</tr>
</tbody>
</table>