DOE Fuel Cell Technologies Office
Hydrogen for Energy Storage

Workshop on Hydrogen Energy Storage
Grid and Transportation Services
Sacramento, California

May 14th & 15th 2014 at the Grand Sheraton Hotel

Dr. Monterey R. Gardiner
Technology Manager
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Fuel Cell Technologies Office
U.S. Department of Energy
• Previous Analysis Efforts by DOE
  • National Laboratories, Hydrogen Technical Advisory Committee

• Past Workshops
  • Flow Cells, Electrolyzers R&D Needs, International

• Energy Systems Integration Facility
  • National Renewable Energy Laboratory

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

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**Value Added Applications**

- Vehicle Fuel
- Fertilizer NH₃
- Emergency BuP FC

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**Frequency Comparison**

- **RED**: 1 MW /∞
- **BLUE**: No H₂ storage
- **SLK**: 1 MW /1 minute of H₂ storage

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**Source**: www.hydrogen.energy.gov/pdfs/review12/mt008_ewan_2012_o.pdf

Hawaii Natural Energy Institute Mitch Ewan, GE Transient PSLF™
Hydrogen is a flexible energy storage option and Power Generation spans the range of microwatts to GW with Hours to Months of Storage Capacity.

Quiet, low emission, low maintenance fuel cells to provide onsite heat and power for easy siting.

Can FCs and Electrolyzer Systems Satisfy Multiple Markets?

(hours / days & seconds / minutes)

H₂ + O₂ Turbine

PEM or SOFC

Data from Sandia Report 2002-1314
Can Ancillary Services be Monetized?

Electrolyzers respond quickly and could provide valuable grid stabilization services. Currently ancillary services have low market values, and low utilization rates. As societies become more dependent on variable generation, the value will likely increase.

Ancillary Service Requirements

- **Response time**: How quickly can you begin responding?
- **Ramp-rate**: How fast can you change your response?
- **Energy capacity** (duration): For how long can you respond?
- **Power capacity**: How much can you provide in response?
- **Min. turndown**: What is your lowest operating point?
- **Startup time**: How long does it take to start up?
- **Shutdown time**: How long does it take to shutdown?

Source: Josh Eichman NREL Fellow
LCOE ($/kWh) from multiple studies: H₂, PbA, NaS, CAES & Pumped Hydro

A wide range of costs have been presented in the past, primarily due to market assumptions and methodology: arbitrage, financials, technology maturity, market type

Sources:

- **HTAC**: S. Thomas, “Estimates of Electricity Costs from Battery and Hydrogen Storage Systems,” paper describing HTAC model.
### From Left to Right Targets: Long, Mid, Near Term FCTO Technology Targets

<table>
<thead>
<tr>
<th>Electrolyzer utilization</th>
<th>Electrolyzer cost</th>
<th>Electrolyzer efficiency</th>
<th>Fuel cell cost</th>
<th>Fuel cell efficiency</th>
<th>Storage (geologic vs tanks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(67%, 50%, 33%)</td>
<td>(380, 460, 2000 $/kW)</td>
<td>(87, 79, 58 %HHV)</td>
<td>(434, 813, 3000 $/kW)</td>
<td>(49, 45, 40 %HHV)</td>
<td>(7, 700 $/kg)</td>
</tr>
</tbody>
</table>

**Electrolyzer Improvements Provide the Largest Benefit: Utilization, Capital Cost, Efficiency**

- **Reaching Midterm targets as a 1st priority, where gains are made**
  - Aboveground storage is more flexible and will reduce project implementation time

**Levelized Cost of Peak Power ($/kWh)**

- $0.7
- $0.8
- $0.9
- $1.0
- $1.1
- $1.2
- $1.3
- $1.4
- $1.5
- $1.6
- $1.7
**Challenges**

- Improved stack performance
- High pressure stack/system components/membranes
- Increase stack size
- Market issues (balance of manufacturing investment and market size)
- Grid integration

**RD&D Needs**

- Improved catalysts
- Improved membranes
- Better anode support media
- Studies of high P electrolysis vs. compression
- Demonstrate large scale viability (MEA, power conversion, etc.)
- Low cost hardware
- Studies determining best markets for electrolysis
- Value proposition for oxygen?
- MW scale demonstration
- Market acceptance of electrolysis

**Additional Market Opportunities (ranked by order of votes)**

1. Power to gas
2. Ancillary grid services (frequency/voltage regulation)
3. Renewable H2 for petroleum refining
4. Forklifts

**RD&D Needs Near Term**

- Study what the additional market opportunities are worth (and size) now and later.
- Create MW scale development program including large scale testing & MW scale test lab w/ low cost or curtailed electricity
- Definition of electrolyzer requirements across applications
- Education (of stakeholders)
- MW-Scale pilots to provide services (regional grids)
- Develop electrolyzer roadmap – prove out costs and critical elements
- Forklifts – Material handling projects don’t have funding for onsite hydrogen production
Workshop Summary Report (March 2012)
by Adam Z. Weber, Lawrence Berkeley National Laboratory
http://energy.gov/eere/fuelcells/flow-cells-energy-storage-workshop

Organizing Committee:
Industry, National Laboratories and DOE:
EERE, ARPA-E, and the Office of Electricity Delivery &
Energy Reliability

International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) –
Hydrogen Storage Workshop November 2012
- Over 100 participants from more than 20 countries
- Provided high level recommendations for hydrogen to be an economic solution to over-generation
- Focus on policy and requirement for multidisciplinary expertise to evaluate and communicate benefits

www.iphe.net/events/workshops/workshop_2012-11.html

Reversible flow cell advantages: energy storage:
- High round-trip efficiency (60 – 90%)
- Power and energy capacity are large and decoupled
- Long cycle life
- Low self-discharge
- Reliable and stable performance

Applying breakthroughs from core fuel cell technologies to improve efficiency, performance, durability, and cost
Future directions include increased cross-cutting activities and collaboration such as through DOE’s new national asset for energy systems integration research, development, and testing.

Future Directions - Energy Systems Integration Facility (ESIF)

Quadrennial Energy Review
Established January 2014

- Four year Cross Federal Agency Effort
- First year will focus on Energy Infrastructure & will Develop a Roadmap to modernize U.S. Energy Infrastructure
- Part of the Presidents Climate Action Plan

http://energy.gov/epsa/initiatives/quadrennial-energy-review-qer
California Zero Emission Vehicle Mandate & Renewable Energy Portfolio Standards

California has aggressive zero emission vehicle and renewable energy generation goals:

→ 1.5M zero emission vehicles by 2025, with infrastructure to support 1M by 2020

→ CA is planning for next steps beyond 33% REPS in 2020, for 2030 (~40% or some other scheme)

California Utilities Commissioned Study
–by Energy & Environmental Economics (E3)

<table>
<thead>
<tr>
<th>Overgeneration Statistics</th>
<th>33% RPS</th>
<th>40% RPS</th>
<th>50% RPS Large Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Overgeneration GWh/yr.</td>
<td>190</td>
<td>2,000</td>
<td>12,000</td>
</tr>
<tr>
<td>Percent of RPS energy%</td>
<td>0.2%</td>
<td>1.8%</td>
<td>8.9%</td>
</tr>
<tr>
<td>Overgeneration frequency Hours/yr.</td>
<td>140</td>
<td>750</td>
<td>2,000</td>
</tr>
<tr>
<td>Percent of hours</td>
<td>1.6%</td>
<td>8.6%</td>
<td>23%</td>
</tr>
<tr>
<td>Extreme Overgeneration Events 99th Percentile (MW)</td>
<td>610</td>
<td>5,600</td>
<td>15,000</td>
</tr>
<tr>
<td>Maximum Observed (MW)</td>
<td>6,300</td>
<td>14,000</td>
<td>25,000</td>
</tr>
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Source: www.ethree.com/documents/California_Utility_Brief_E3_Study_Final.pdf

Anticipated FCEVs on the Road, 2011-2017, 2012 CAFCP Roadmap

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<tbody>
<tr>
<td>2010-2011</td>
<td>253</td>
<td>312</td>
<td>430</td>
<td>1,389</td>
<td>53,000²</td>
<td></td>
</tr>
</tbody>
</table>

Source: cafcp.org/carsandbuses/carroadmap

Electric drive transportation fuel demand can support a grid with high variable generation

- Ca-SB1505 requires 33% RE H2 for state funded stations, & all infrastructure after 3500 tons/y (~18K FCEV)
- 33% RPS ~1.3GW electrolyzer with 1.5% CF & Storage!
- 190GWh results in 8.5 Ton/d or 3.1M kg/y (60kWh/kg)
- 16K FCV- 200 kg/yr (50 mi/kg), ~50K FCV with 33% RE H2
- Electric drive- EV 0.25 kWh/mi & FCV 0.8-1.2 kWh/mi
  - 2.5 MWh/EV-year & ~ 10 MWh/FCV-year
Identify benefits & opportunities for commercial hydrogen energy storage applications which support: Grid Services, Variable Electricity Generation, Hydrogen vehicles

**Key topics:** (1) Business models and early applications, (2) Specific policy barriers and incentives, (3) Modeling and econometric approaches, and (4) Potential opportunities for effective demonstrations

Thank you!

Fuel Cell Technologies Office
http://energy.gov/eere/fuelcells/fuel-cell-technologies-office

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202-586-1758
Reaching long term technology targets shows levelized cost of electricity could be $\frac{1}{2}$ of new pumped hydro or advanced batteries e.g. Na-S battery.
Using static market assumptions, H₂-storage costs are competitive to battery systems for long duration storage needs, costs increase at a slower rate (compared to battery systems).
Underground hydrogen storage is competitive with most battery options at medium and long term

Assumptions:
10MW FC, 40 MWhr storage, %10 free electricity, 33.3% capacity factor electrolyzer (8 hr/d), FC operating 4 hr/d
California Public Utilities Commission
AB 2514 (2010)
1. To open a proceeding to determine appropriate targets, if any, for each load-serving entity to procure viable and cost-effective energy storage systems.
2. By October 1, 2013, adopt an energy storage procurement target, if determined to be appropriate, to be achieved by each LSE by December 31, 2015, and a 2nd target to be achieved by December 31, 2020.
3. “[T]he commission may consider a variety of possible policies to encourage the cost-effective deployment of energy storage systems, including refinement of existing procurement methods to properly value energy storage systems.”

Rice Project: 150 MW CSP plant in Sonoran Desert, CA
- Developer (SolarReserve LLC) will sell power to PG&E for 25 years (beginning June 1, 2016).
- 10 hours of energy storage.
- **Cost = $600 million.**
- First commercial-scale system in CA to include energy-storage capability.

Similar project (Crescent Dunes) by SolarReserve, near Tonopah, NV- operational 2013
- 110 MW molten salt power tower. (+$10 million per year in salaries and operating costs)
- Will provide energy for NV Energy, Inc.
Summary - Total Installed Cost $ / kW

NREL-2009: High, Average, Low Assumptions
FC + Electrolyzer + Above Ground Storage 4 hr

$4430/kW
$1850/kW
$1370/kW

Range of Costs Due to: 1. Technology; 2. Hours of Storage; 3. Maturity
Hydrogen & Fuel Cells for Energy Storage

Increasing renewable energy utilization while supporting the grid!

Alternative Storage Technologies and Necessary Assumptions

• Battery Storage Systems (near 90% efficiency)
  – Power conditioning system: AC-DC rectifier, DC-AC output switchgear
  – Battery bank, and balance of plant

• Hydrogen Storage Systems
  – Electrolyzer, underground storage cavern, compressor system
  – Fuel cell plus DC-AC inverter

• Common Model Assumptions
  – e⁻ stored 8 hr/d, 10 MW power 4 hr/ 40 MWhr,
  – 10% e⁻ “free” balance at 6c/kwh for 8 hr,
  – Battery/electrolyzer sized to meet storage needs

• Financial Assumptions: 10% ROI and …:
  – Battery O&M 2% of Capital cost
  – 2.5%/y compressors, 2.2%/y electrolyzer, 2%/y FC
  – Storage time varied from 4 hr to 2 months
  – Component replacement fund 6.2%/yr interest
LCOE Cost Assumptions used by NREL

-Assumptions follow FCTO MYRDD goals, with more aggressive metrics Long-Term
-Long-Term R&D could allow Reversible FC’s achieving high efficiency and low cost

<table>
<thead>
<tr>
<th>System Description</th>
<th>Near-Term</th>
<th>Mid-Term</th>
<th>Long-Term</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distributed Fuel Cell</td>
<td>Central Fuel Cell</td>
<td>Central CC-Turbine</td>
</tr>
<tr>
<td>Power rating (MW)</td>
<td>10 150 150</td>
<td>10 150 150</td>
<td></td>
</tr>
<tr>
<td>Energy storage capacity</td>
<td>4 hours 1 week 1 week</td>
<td>4 hours 2 weeks 2 weeks</td>
<td></td>
</tr>
<tr>
<td>H2 Storage type</td>
<td>Terrestrial Salt-dome Salt-dome Salt-dome</td>
<td>Terrestrial Salt-dome Salt-dome</td>
<td></td>
</tr>
</tbody>
</table>

**Operation**

NREL Model: capital recovery factor 12%, maintenance 5% of capital cost, ~5 cents/kWh e-

<table>
<thead>
<tr>
<th>Operation</th>
<th>Near-Term</th>
<th>Mid-Term</th>
<th>Long-Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyzer efficiency (% HHV)</td>
<td>58% 58% 58%</td>
<td>79% 79% 79%</td>
<td>87% 87% 87%</td>
</tr>
<tr>
<td>Generator efficiency (% HHV)</td>
<td>40% 51% 45%</td>
<td>70% 49% 70%</td>
<td>49% 49% 70%</td>
</tr>
<tr>
<td>Discharge hours (hours/day)</td>
<td>4 4 4</td>
<td>4 4 4</td>
<td>4 4 4</td>
</tr>
<tr>
<td>Charge hours (hours/day)</td>
<td>8 8 8</td>
<td>12 12 12</td>
<td>16 16 16</td>
</tr>
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**Installed Capital Costs**

<table>
<thead>
<tr>
<th></th>
<th>Near-Term</th>
<th>Mid-Term</th>
<th>Long-Term</th>
</tr>
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<tbody>
<tr>
<td>Electrolyzer ($/kW)</td>
<td>2,000</td>
<td>2,000</td>
<td>-</td>
</tr>
<tr>
<td>Power generation ($/kW)</td>
<td>3,000</td>
<td>783</td>
<td>655</td>
</tr>
<tr>
<td>H2 Storage ($/kg)</td>
<td>700</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Total system cost ($000)</td>
<td>76,668</td>
<td>1,120,286</td>
<td>161,283</td>
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</table>

**Feedstock Cost**

<table>
<thead>
<tr>
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<th>Near-Term</th>
<th>Mid-Term</th>
<th>Long-Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of electricity ¢/kWh</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Percent of free electricity</td>
<td>10%</td>
<td>20%</td>
<td>30%</td>
</tr>
<tr>
<td>Blended cost of electricity ¢/kWh</td>
<td>5.4</td>
<td>4.8</td>
<td>4.2</td>
</tr>
</tbody>
</table>
Reversible Flow Cells

High efficiency energy storage that leverages existing fuel cell technology

Advantages of reversible flow cells for energy storage:
• High round-trip efficiency (60 – 90%)
• Power and energy capacity are large and decoupled
• Long cycle life
• Low self-discharge
• Reliable and stable performance

Applying breakthroughs from core fuel cell technologies would improve efficiency, performance, durability, and cost
Foot Print Hydrogen & 1-2 MW electrolyzer: 24 to 2000 MWh (1-90 d) [e- consumption]

~24 MWh day input capacity for electrolyzer (1MW, ~50 kWh/kg)  
~450 kg/day (430 - 480 kg )
30 MW wind farm, 33% Capacity Factor ~24MWh average output, Liquefaction +10-15 kWh/kg

Olympic Swimming pool 50M X 25M X 2M  
2500 M³, (~2XISO 170 M³) 40 days@100bar

<table>
<thead>
<tr>
<th>24 MWh/d</th>
<th>10 bar</th>
<th>50 bar</th>
<th>100 bar (+~1 kwh/kg)</th>
<th>350 bar (+2-3 kwh/kg)</th>
<th>Liquid (+10-15 kwh/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>~kg/m³ / M³</td>
<td>0.8</td>
<td>4.5</td>
<td>8</td>
<td>24</td>
<td>70</td>
</tr>
<tr>
<td>1 day</td>
<td>562</td>
<td>100</td>
<td>56</td>
<td>19</td>
<td>6</td>
</tr>
<tr>
<td>10 day</td>
<td>5625</td>
<td>1000</td>
<td>562</td>
<td>188</td>
<td>64</td>
</tr>
<tr>
<td>40 day</td>
<td>22500</td>
<td>4000</td>
<td>2250</td>
<td>750</td>
<td>257</td>
</tr>
<tr>
<td>90 day</td>
<td>50625</td>
<td>9000</td>
<td>5063</td>
<td>1688</td>
<td>579</td>
</tr>
</tbody>
</table>

Proton: Open-frame skid modular plant configuration, Transition from previous fully-packaged designs

1MW ~2X 40 ft iso container (40X8X8.5 feet)  
Metric-Meter (12.2X2.4X2.9) plus set back

Aug. 2013- Hydrogenics  
2MW Power-to-Gas Demonstration Plant  
Falkenhagen, Germany
2012 Landscape for Energy Storage

- Pumped hydro dominates (location constrained)
- Followed by compressed air energy storage
- Other technologies ramping quickly

U.S. Pumped Hydro:
19 GW Installed
31 GW Planned
Versus ~250MW Other Storage

Over 99% of total storage capacity

Source: Fraunhofer Institute, EPRI - 2012
ESI Energy Systems Integration

**Vision**
- EE and RE technologies are integrated into the energy system in a safe, reliable, and cost-effective manner at a relevant scale to support the nation’s goals of 80% clean electricity by 2035 and reducing oil imports by 33% by 2025.

**Project Goal**
- Conduct research and testing to characterize the building and grid services related to building loads, electric vehicles, and DER,
- Develop holistic approaches to increasing the hosting capacity of EE and RE technologies on the grid.
Activities Proposed in Area 1 for Lab Directed Work, Lab Call, or Industry Solicitation

Physical Characterization of Electrolyzer Capabilities: What ancillary services can electrolyzers provide to the grid and to microgrid control entities? What range of responses or other characteristics do stakeholders (utilities, utility commissions, others) need? How can these responses be prioritized for grid services?

DOE ACTIVITIES – Develop a cost reduction road map for FCTO based energy storage technologies:
1. Workshop on Electrolyzer R&D gaps and new market opportunities (February)
2. Workshop on FCTO Opportunities for Energy Storage (March)
3. Present results of Workshop-ES at FCTO Annual Merit Review (June)
4. Q3 Draft FCTO Hydrogen for Energy Storage R&D Roadmap

NREL ACTIVITIES – Support development of and characterize MW scale electrolyzer
1. Develop characterization protocols to evaluate electrolyzers’ response to grid signals and load-following renewable electricity inputs
2. Physically test devices to determine impact to durability under variable operation
3. Develop models of electrolyzers for high penetration simulations
4. Report baseline characterization of specific grid support capabilities
5. Develop transition plan for test equipment utilization in FY15 with a minimum 50% industry cost share

INDUSTRY –
1. Provides 125 kW electrolyzer stack installed at 250 kW (capable) test bed
2. Review characterization protocols with utilities
3. Demonstrate capabilities of electrolyzers to utilities and regulators

1.0 Physical Characterization- establish a flexible, testing environment for variable-powered stack operation and advanced R&D on electrolyzer balance of plant (BoP) components. With a goal of plug-n-play installations to reduce cost and added value to grid services market. This pre-solicitation effort establishes a functional electrolyzer test bed for utility and industry, and other national laboratory grid integration RD&D efforts.

1.2 -Conduct stack- and system-level testing to demonstrate stack operation and recommend BoP optimization to aid in the monetization of ancillary services for electrolyzer systems with utility stakeholders to gain confidence and industry buy-in of capabilities.

1.3 -Report detailed characterization of large-scale electrolyzers for providing grid services. As part of this task, utilities and regulators will be invited to ESIF to witness first hand how these technologies can be used to provide grid services.
Activities Proposed in Area 2 for Lab Directed Work, Lab Call, or Industry Solicitation

1.0 Physical Characterization of EE & RE Technologies

2.0 Comm., Information, Computation Infrastructure

3.0 Developing Holistic Grid Services

Increasing & Enhancing the Hosting Capacity

Development of Data, Communication, and IT “standards” to Support Open Integration

Communications, Information, and Computational Interface: What data are available and needed? How can we standardize data communication and leverage existing work in this area? How do we verify that the devices are able to share and act on data transmitted?

DOE ACTIVITIES – Support development of common data interoperability/taxonomies-classifications. Collaborate with industry to develop standard data maps, interoperability protocols for the various market structures. Hydrogen provides three energy vectors: electricity, vehicle fuel and thermal energy. We will identify opportunities at the boundaries of these vectors, e.g. leveraging energy storage at refueling-charging stations and the high value of transportation fuel.

NREL ACTIVITIES
1. Develop Communications, Information, and Computational connections (communication layer) for integrated system experimentation
2. Develop an advanced utility interface (AUI) to accept communication signals, process and deliver control commands to electrolyzer stack and BoP subsystems.
3. ($100K) Support Virtual connection between ESIF and INL Real-time digital simulator (RTDS) – allows integration of ESIF RTDS to much larger RTDS in order to simulate much larger power systems

Industry
1. Provide input regarding the interoperability of technologies
2. Provide input on cross industry communications structures while defining value streams resulting from repurposing equipment and increasing asset utilization

Grid market and operational signals
Open, Flexible Communications, Information, and Computation
Electrolyzer signals
Other devices (e.g. wind)

2.0 C. Communication (link INL’s RTDS systems) - connect to INL’s 138kV loop and 3 region utility intersection, further discussion with other Offices anticipated
Activities Proposed in Area 3 for Lab Directed Work, Lab Call, or Industry Solicitation

DOE ACTIVITIES
1. Develop use cases and needs (e.g. residential scale energy system, distribution systems with high penetrations of renewable energy, integrated wind/hydrogen system) for deployments of electrolyzers and fuel cells at scale

NREL ACTIVITIES
1. Implement and demonstrate supervisory communication/control platform to optimize electrolyzers with multiple EERE technologies; includes a customer (energy manager) friendly interface
2. Analyze and refine (at ~1/8 scale) the value proposition of MW electrolyzers and provide a prioritized list of grid services and other energy vectors (vehicle fuel, thermal- power to gas H₂ + natural gas pipelines)
3. Under Discussion: Demonstrate & describe capabilities of integrated systems to utilities and regulators
   1. Explore gas storage cost reduction where applicable
   2. Stand alone wind and large scale electrolyzers for vehicle fuel
   3. Opportunities for refueling station operation or multiple small scale (~kW range) FCs to support the grid

INDUSTRY
1. Provide constraints and parameters for value stream proposals
2. Review use cases and results (especially electrolyzer performance)
3. Recommend demonstration sites and potential projects in FY15
Transactive Energy
Physical energy is commingled with information and allocated value.

Transactive Based Control
Transaction based controls are a key enabler – control the physical, use the logical, and contribute to settling the financial.

Integration of Renewable Generation & DER

Customer-Side Applications

Grid Control & Optimization Systems

INTEGRATED DER REFERENCE DOCUMENT

TRANSACTIVE REFERENCE DOCUMENT

AGREEMENT ON INTEGRATED INTEROPERABILITY
Hydrogen-based storage systems can provide storage at costs that are 10x less than battery systems, because power and energy scale separately.

Liquid tanker 4,000 kg, 60 MWh final electricity via fuel cell, $20,000 vehicle fuel at $5/kg or $3000 of electricity at 0.05$/kWh. 280 MWh with transmission (without line losses or opportunity costs or congestion uncertainty) is $14,000 at $0.05/kWh).

280 MWh of partially curtailed electricity to provide:
$20,000 of hydrogen vehicle fuel at $5/kg, 1 kWh/mile
$14,000 of electricity sold via transmission line using 280 MWh at $0.05/kWh, and $28,000 at 0.10/kwh
$3000 (60 MWh at $0.05/kWh) with added value of very high power-quality, and reliable electricity that is quiet and has zero local emissions produced onsite.

~$9000 at $0.15/kWh Provided via hydrogen and liquefaction and back to electricity (Backup power, resiliency, high density energy storage applications) *does not take into account production costs, only target sales cost.

Battery systems: Power and Energy scale together; More energy storage = more batteries; Marginal cost of storage $1400/kWhr
Electrolyzer Response Time Testing

All devices are VERY responsive, and will meet ancillary service needs

- Resulting Response time for ramp-up and ramp-down tests for both PEM and Alkaline units at NREL

![Response Time Graph](chart.png)

Source: Josh Eichman NREL Fellow
Power set-point was changed (PEM unit shown below)
  - Ramp Up: 25%, 50%, and 75% → 100%
  - Ramp Down: 100% → 75%, 50% and 25%

Trigger at 0.02 seconds
Response (±1% max current)

Samples taken every 0.0002 seconds

Source: Josh Eichman NREL Fellow
Larger hydrogen refueling station capacities (100 kg to 400 kg) and lower costs Result in much higher revenues & a near market case for Electrolyzers to support the grid

- **Comparison of annual revenue and cost**

  - **2012 California data**
  - **High Estimate**
  - **Low Estimate**
  - **$10/kg**
  - **$3.1/kg**

Source: Josh Eichman NREL Fellow
Electrolyzer Flexibility Tests

- Electrolyzers testing at the National Wind Technology Center
  - Startup and Shutdown
  - Minimum Turndown
  - Response Time
  - Ramp Rate
  - Frequency Response

<table>
<thead>
<tr>
<th></th>
<th>PEM</th>
<th>Alkaline</th>
</tr>
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<tbody>
<tr>
<td>Manufacturer</td>
<td>Proton OnSite</td>
<td>Teledyne Technologies</td>
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<tr>
<td>Electrical Power</td>
<td>50kW (208VAC)</td>
<td>40kW (480VAC)</td>
</tr>
<tr>
<td>Rated Current</td>
<td>155A per stack</td>
<td>220A 75 cell stack</td>
</tr>
<tr>
<td>Stack Count</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Hydrogen Production</td>
<td>12 kg/day</td>
<td>13 kg/day</td>
</tr>
<tr>
<td>System Efficiency at Rated Current</td>
<td>68.6 (kWh/kg)</td>
<td>95.7 (kWh/kg)</td>
</tr>
</tbody>
</table>
1. Lessons learned and data from Canada others regarding wind curtailment and power to gas opportunities
2. DC-DC efficiency gains (~15% inverter loss DC-AC-DC)
3. Real time digital simulator-INL-NREL
4. NG-FC-PV Synergies
5. Investigate business case for residential FCs (60K 750W sold in Japan)
6. ESIF as test bed for qualified H-Prize entries
7. H2 infrastructure with disaster resilience to provide EV charging and H2 refueling
8. MW scale biomass fed electrolyzer development (Proton)

Beyond Technology Status

CA Public Utilities Commission Rate Making Order R10-12-007

Barriers to Energy Storage Development - A Lack of:
1. Definitive System Need
2. Cohesive Regulatory Framework
3. Evolving Markets and Market Product Definitions
4. Resource Adequacy Accounting
5. Cost Effectiveness Evaluation Method
6. Cost Recovery Policy (cost /market based)
7. Cost Transparency and Price Signals
8. Commercial Operating Experience
9. Well-defined Interconnection Processes
1.1 MW Hydrogen Plant

Plant Total = 250 m²

230 m²/MW
Combine Cycle Turbine Plant

600 MW Natural Gas plant

<table>
<thead>
<tr>
<th>Component</th>
<th>Area</th>
<th>Area/MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant</td>
<td>50,000 m²</td>
<td>83 m²/MW</td>
</tr>
<tr>
<td>Ponds</td>
<td>120,000 m²</td>
<td>200 m²/MW</td>
</tr>
<tr>
<td>Total</td>
<td>170,000 m²</td>
<td>283 m²/MW</td>
</tr>
</tbody>
</table>
89 MW Natural Gas plant

- Plant = 17,000 m², 190 m²/MW
- Ponds = 30,000 m², 340 m²/MW
- Total = 170,000 m², 530 m²/mW
Managing Expectations

- Utility Owner's focus on cost
  - Consumers: resilience, reliability & cost of outages or poor quality electricity
- Storage is one of the last options for supporting the electric grid

Flexibility Supply Curve

<table>
<thead>
<tr>
<th>Task</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output smoothing</td>
<td>Intermittent ~ second</td>
</tr>
<tr>
<td>Load-leveling</td>
<td>Daily 4-12 h</td>
</tr>
<tr>
<td></td>
<td>Weekly 40-60 h</td>
</tr>
<tr>
<td></td>
<td>Seasonal 3 month</td>
</tr>
<tr>
<td>Peak Shaving</td>
<td>180-10000 s</td>
</tr>
<tr>
<td>Spinning reserve</td>
<td>30-300 s</td>
</tr>
<tr>
<td>Voltage stabilisation, frequency regulation</td>
<td>0.5-120 s</td>
</tr>
<tr>
<td>Countermeasure against supply disruption</td>
<td>0.12-0.2 s</td>
</tr>
<tr>
<td>Improvement of stability</td>
<td>0.02-0.2 s</td>
</tr>
</tbody>
</table>


In 2011, U.S. consumed 3,856 TWh of electricity (10.5 TWh/day).
Source: U.S. Energy Information Administration

Storage amounted to ~23 GW, at ~24 hours ~ 550 GWh (4% is ~30 M kg H₂).
Curtailed Wind: 10% assumption is too low

- Wind growth has been rapid (‘07-’11)
  - NYISO, PJM, MSIO more than 250%, SPP, CAISO, ERCOTT, BPA ~150%
- ERCOTT has ~2500GWh/yr curtailed
  - Western portion generation, eastern portion demand
  - Transmission under construction, Dispatchable Intermittent Resources will alleviate this

Wind production in ERCOT tripled from 2007 to 2011
Total curtailments increased in each year from 2008 to 2011

**Wind Installed Capacity in MW's**

<table>
<thead>
<tr>
<th>Region</th>
<th>2002</th>
<th>2007</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>NYISO</td>
<td>763%</td>
<td>997%</td>
<td>248%</td>
</tr>
<tr>
<td>PJM</td>
<td>997%</td>
<td>997%</td>
<td>997%</td>
</tr>
<tr>
<td>SPP</td>
<td>144%</td>
<td>997%</td>
<td>997%</td>
</tr>
<tr>
<td>CAISO</td>
<td>43%</td>
<td>43%</td>
<td>43%</td>
</tr>
<tr>
<td>ERCOT</td>
<td>266%</td>
<td>266%</td>
<td>266%</td>
</tr>
<tr>
<td>MISO</td>
<td>456%</td>
<td>456%</td>
<td>456%</td>
</tr>
<tr>
<td>BPA</td>
<td>171%</td>
<td>171%</td>
<td>171%</td>
</tr>
</tbody>
</table>

*U.S Total Installed Capacity of Wind in the year 2002: 4,822 MW
U.S Total Installed Capacity of Wind in the year 2007: 17,135 MW
U.S Total Installed Capacity of Wind in the year 2011: 46,440 MW
Growth rates shown for each region is % growth from the previous reported year.*

**Wind production and curtailment: 2010 vs. 2011**

- **Wind Generation**
- **Local Curtailment**
- **Zonal/Nodal Curtailment**

2500 GWh/yr →→

*Source: SNL, ERCOT*
Hydrogen technologies could provide many ancillary services for grid stability. Barriers remain: further technical validation and monetizing value to the grid through market mechanisms (FERC, CA Energy Commission).

<table>
<thead>
<tr>
<th>Service</th>
<th>Backup Power (In aggregate)</th>
<th>Tri Gen. (waste-water/sofc-mcfc)</th>
<th>Stationary PEM</th>
<th>Electrolyzers</th>
<th>Bulk H₂ Storage 10MW (4 to 168 hr)</th>
<th>Vehicle+ Fuel Demand (100 to 1000 kg/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spinning/Non-Spinning Reserves</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>TBD</td>
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<tr>
<td>Load Leveling (storage)</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Peak Shaving (gen)</td>
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<td></td>
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<tr>
<td>Voltage Stabilization</td>
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<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
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<tr>
<td>Frequency Regulation</td>
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<td>✓</td>
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<td>Black Start</td>
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<td>TBD</td>
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<tr>
<td>T&amp;D Deferral</td>
<td>TBD</td>
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<td>✓</td>
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</tr>
<tr>
<td>Resilience/Backup Power</td>
<td>✓</td>
<td>TBD</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>TBD</td>
</tr>
</tbody>
</table>