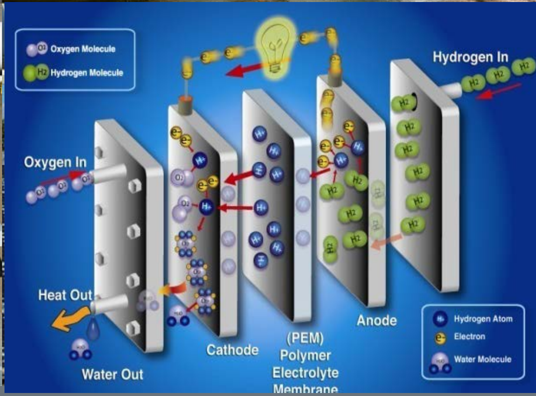
Hydrogen Energy Storage: Experimental analysis and modeling

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

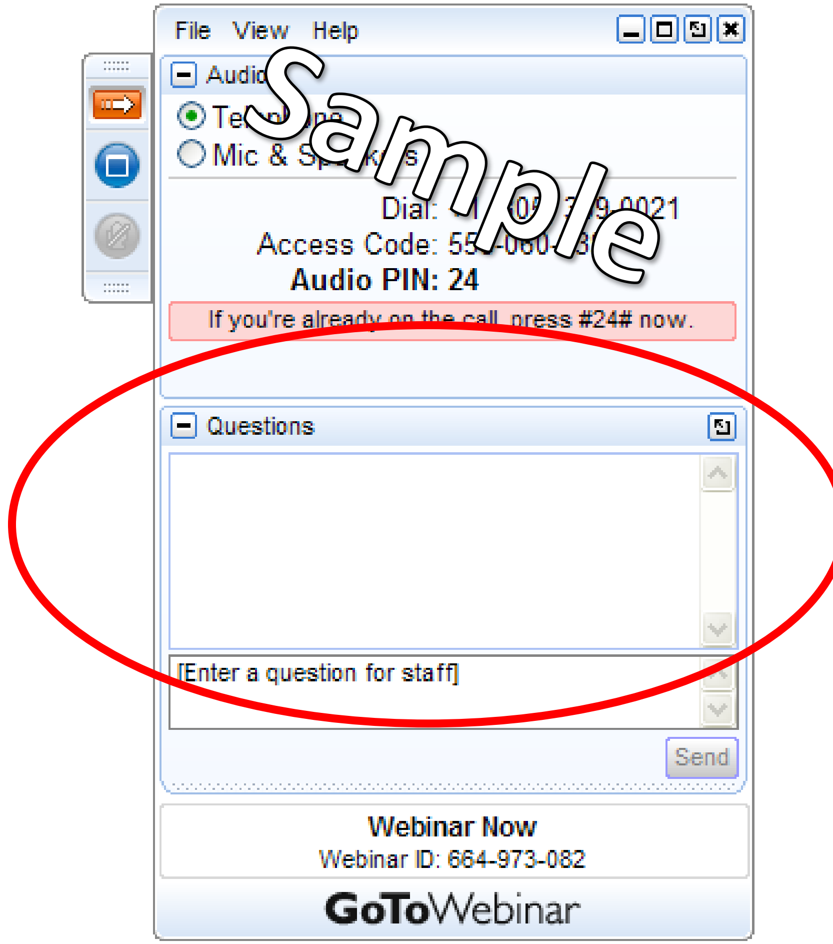



Monterey Gardiner

U.S. Department of Energy
Fuel Cell Technologies Office

Question and Answer

- Please type your question into the question box



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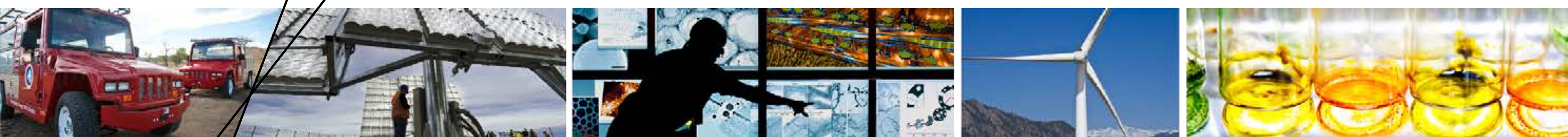


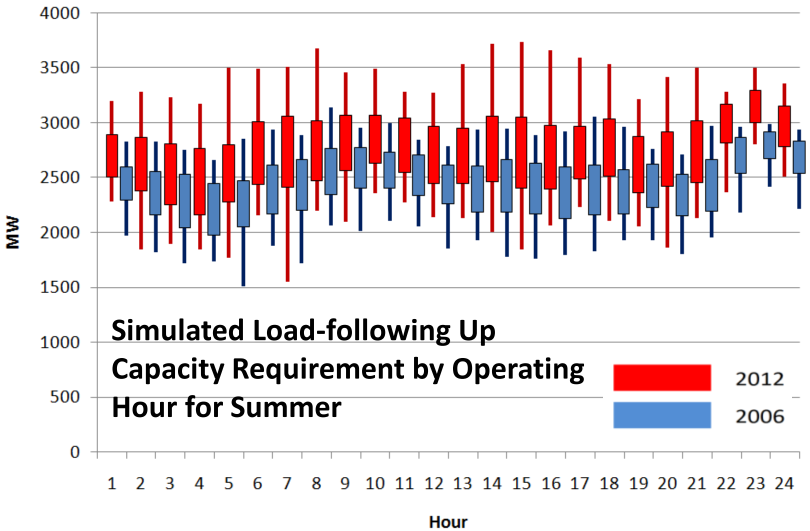
FCTO Webinar

Josh Eichman, PhD

8/19/2014

Motivation for hydrogen energy storage

- **Drivers**
  - More renewables bring more grid operation challenges
  - Environmental regulations and mandates
- **Hydrogen can be made “dispatch-ably” and “renewably”**
- **Hydrogen storage can enable multi-sector interactions with potential to reduce criteria pollutants and GHGs**



Source: GE Energy Consulting (2010). Integration of Renewable Resources: Operational Requirements and Generation Fleet Capability at 20% RPS, CAISO, PNNL, PLEXOS, Nextant.

Source: NREL 00560.

Spoiler Alert

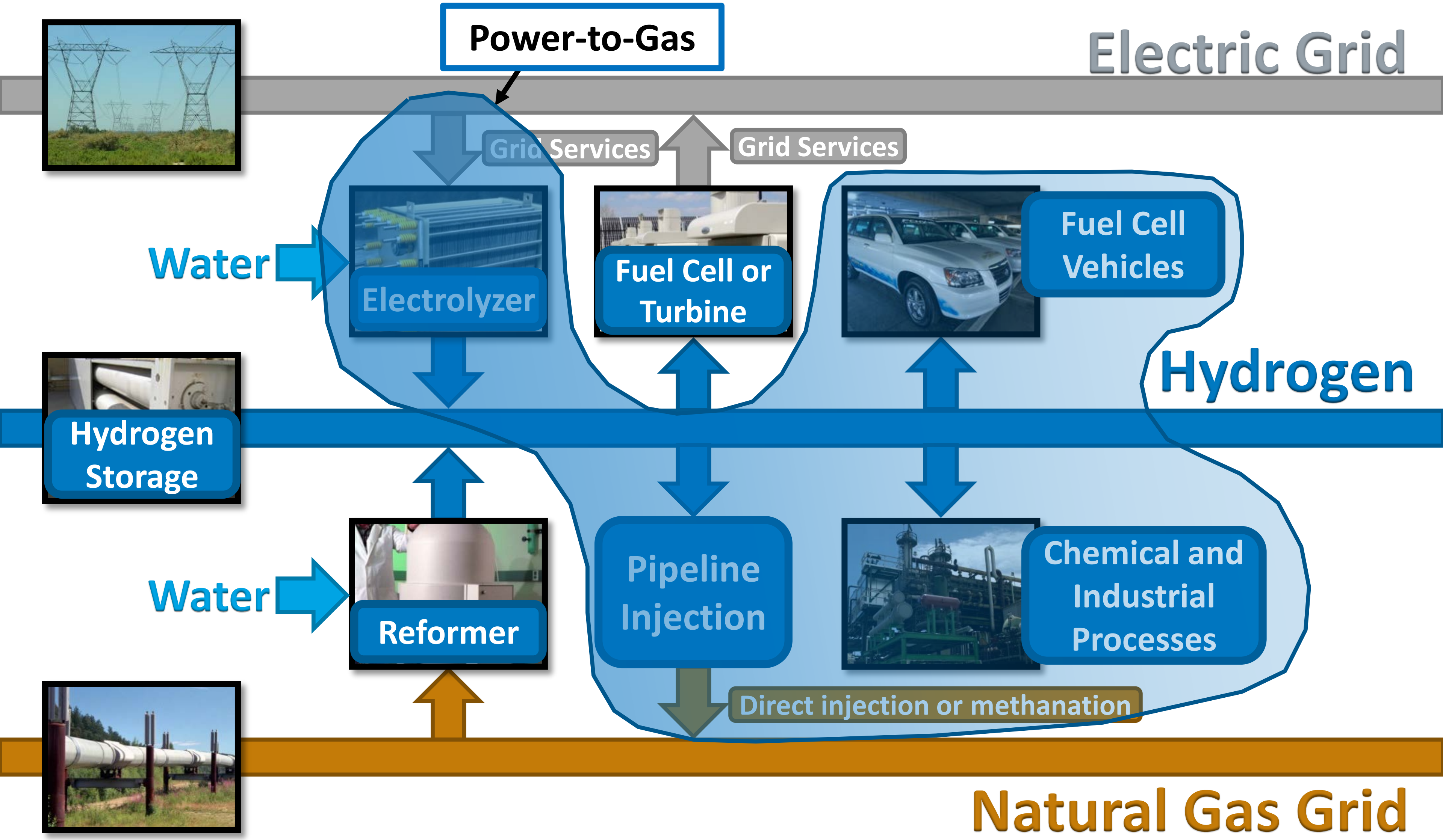
Show that hydrogen technologies…

1. Can be operated flexibly and in a variety of configurations
2. Can enable interactions between multiple sectors
   – Electric, transport, heating fuel and industrial supply
3. Can participate in electricity markets which improves competitiveness and further enables renewables

Outline

- **Hydrogen System Configurations**
- **Grid Operation Requirements**
- **Experimental flexibility tests**
- **Modeling methodology and results**
  - Techno-economic comparison
  - Energy capacity sensitivity analysis
  - Impacts from increased renewables (backup slides)
  - Impacts on larger grid system (backup slides)
- **Recent hydrogen energy storage Workshop**
- **Conclusions**

Hydrogen System Configurations



Source: (from top left by row), Path 26 Wikipedia GNU license; Matt Stiveson, NREL 12508; Keith Wipke, NREL 17319; Dennis Schroeder, NREL 22794; NextEnergy Center, NREL 16129; Warren Gretz, NREL 09830; David Parsons, NREL 05050; and Bruce Green, NREL 09408

Hydrogen storage and Power-to-gas (PtG) projects

- **Hydrogen Projects: 41 realized and 7 planned as of 2012**
  - Germany (7) (5 planned)
  - USA (6)
  - Canada (5)
  - Spain (4)
  - United Kingdom (4) (1 planned)
  - etc.

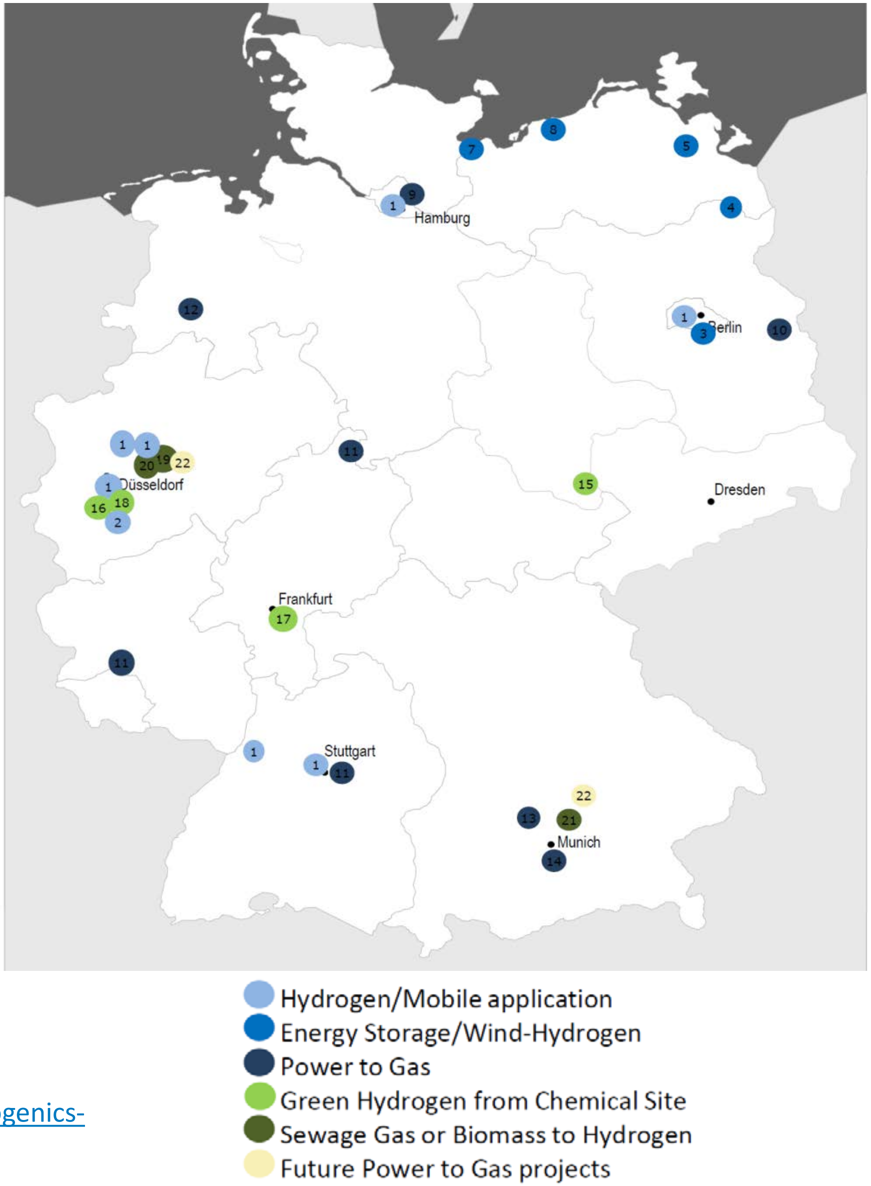
Source: Gahleitner, G. (2013). "Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications." International Journal of Hydrogen Energy 38(5): 2039-2061.

- **Germany has 22 green hydrogen and PtG projects as of 2012 (see figure)**

Source: www.gtai.de/GTAI/Content/EN/Invest/_SharedDocs/Downloads/GTAI/Info-sheets/Energy-environmental/info-sheet-green-hydrogen-power-to-gas-demonstrational%2520projects-en.pdf

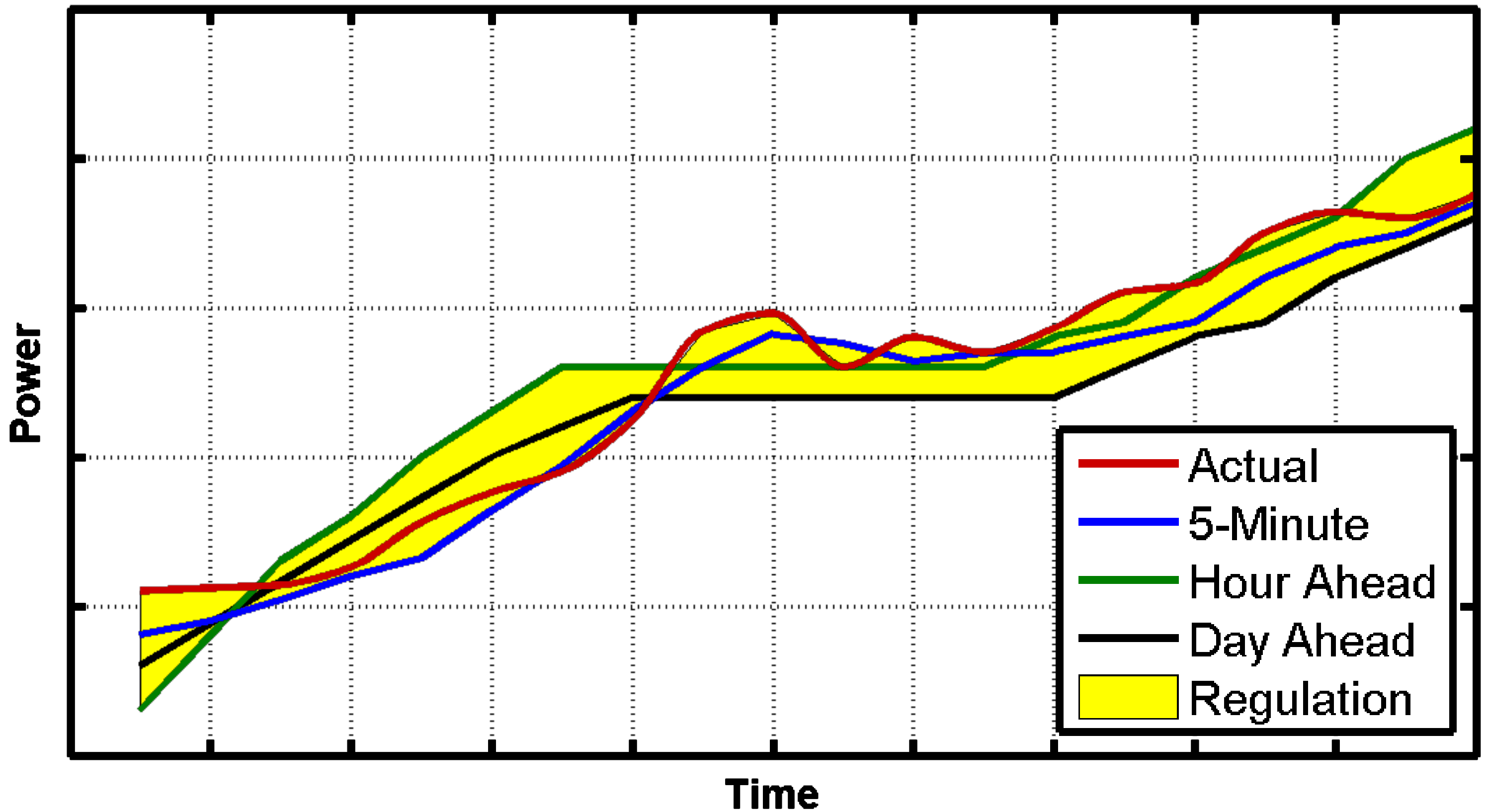
- **Just Announced: 2 MW Power-to-Gas project planned for Ontario, Canada**
  - Acts as energy storage for grid management and regulation provision

Source: www.hydrogenics.com/about-the-company/news-updates/2014/07/25/hydrogenics-selected-for-2-megawatt-energy-storage-facility-in-ontario



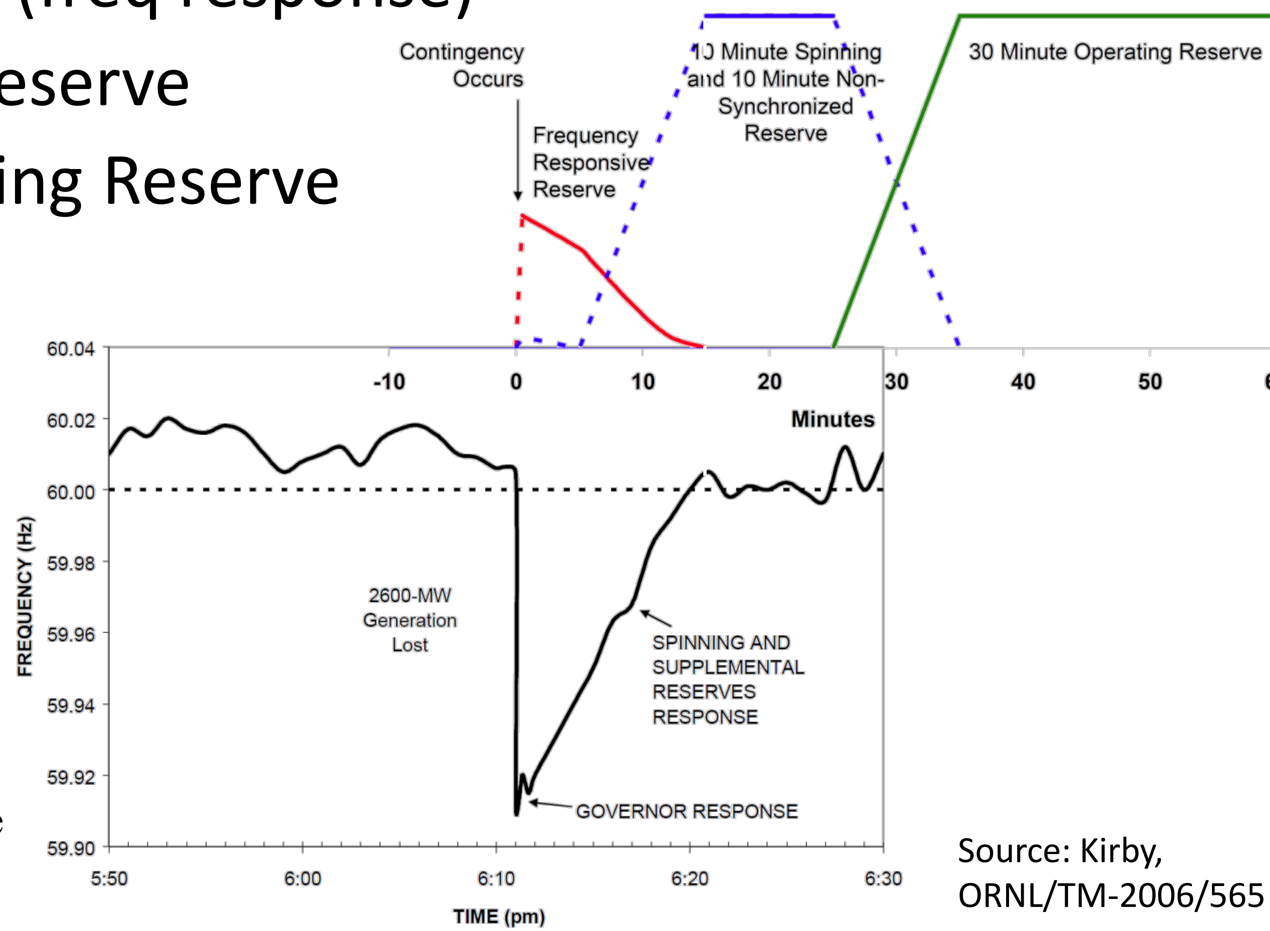
Grid Operation Requirements

- **Electricity demand must closely balance production**



Grid Operation Requirements

- **Ancillary Services**
  - Load Following
  - Regulation (freq response)
  - Spinning Reserve
  - Non-Spinning Reserve
  - Other Reserves
  - Voltage Support
  - Black Start



Example: 2,600 MW are dropped at 6:11 PM

Source: Kirby, ORNL/TM-2006/565

Capacity Markets

- **Sufficient capacity must be acquired**
  - Capacity markets are used to achieve resource adequacy targets
  - Ensures new generation is built (i.e., long-term)
  - Ensures installed generators make sufficient money to pay for capital costs.
- **Cost of New Entry (CONE)**
  - Equivalent to purchasing a new combustion turbine
  - Assume $150/kW-year

Source: Pfeifenberger, J.P.; Spees, K.; Newell, S.A. 2012. Resource Adequacy in California. The Brattle Group

Grid Operation Requirements

- **Market value varies for services provided**
  - Energy
    - Electric Price
  - Ancillary Services
    - Load-Following Up/Down
    - Regulation Up/Down
    - Spinning Reserve
    - Non-Spin Reserve
    - Voltage Support
    - Black Start
  - Capacity
    - $150/kW-year

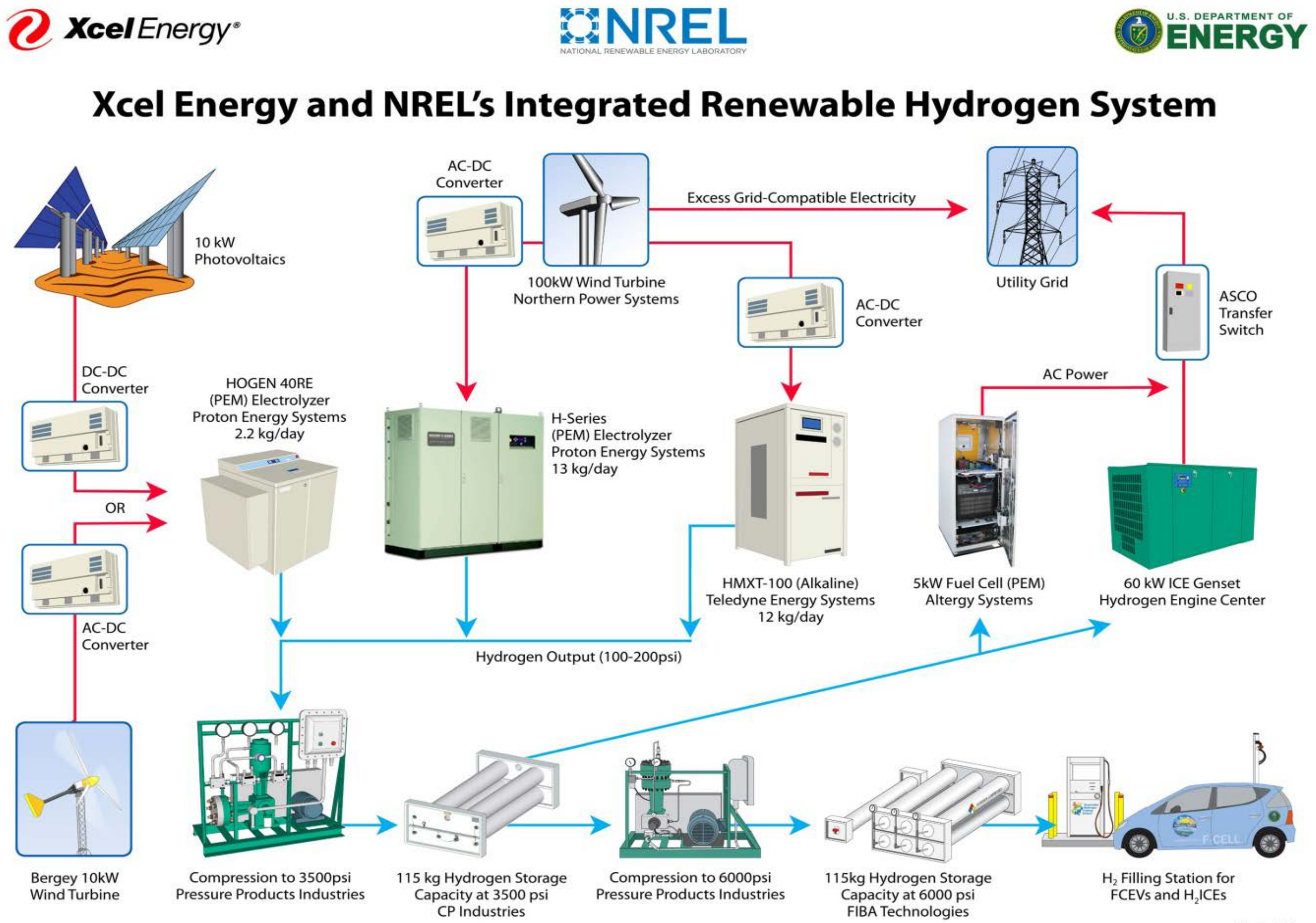
California Historical Market Clearing Prices (CAISO 2012)

Source: Pfeifenberger, J.P.; Spees, K.; Newell, S.A. 2012. Resource Adequacy in California. The Brattle Group

Wind to Hydrogen Project

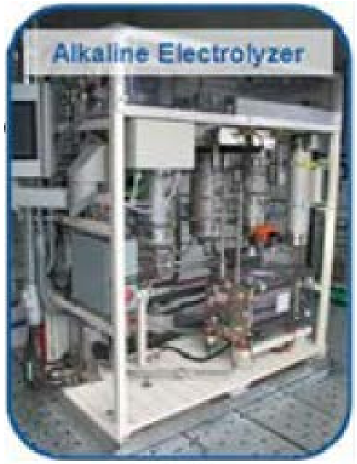
- **Flexibility testing is performed at the National Wind Technology Center**

- **Renewable Integration**
- **Responsive loads (demand response)**
- **Energy Storage**
- **Multiple outputs streams**
    - Electricity
    - Transport fuel
    - Industrial gas



Electrolyzer Flexibility Tests

- **Testing explored several parameters**
  - Startup and Shutdown
  - Minimum Turndown
  - Response Time
  - Ramp Rate
  - Frequency Response

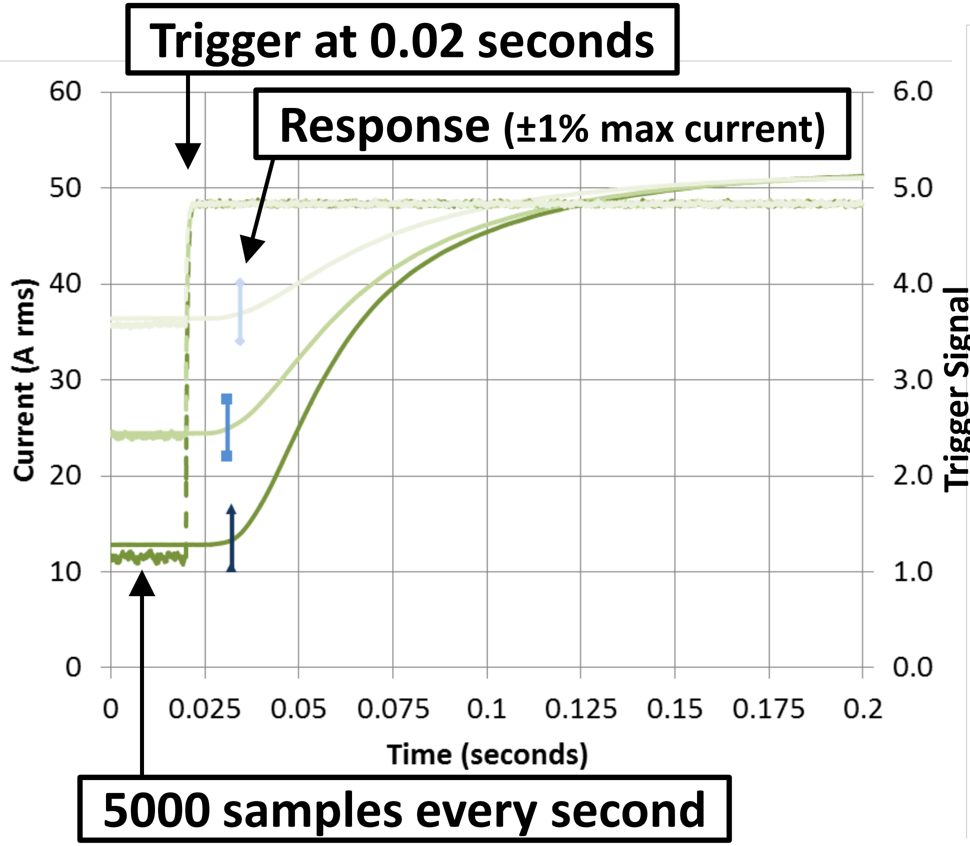


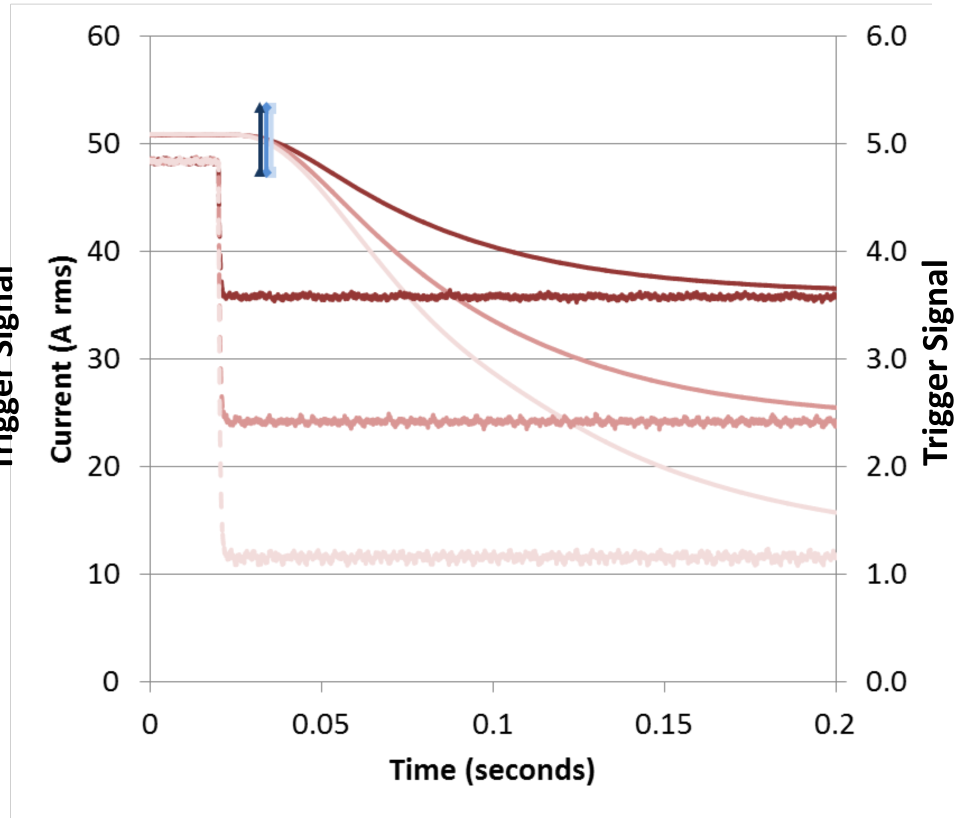
	PEM	Alkaline
Manufacturer	Proton OnSite	Teledyne Technologies
Electrical Power	40kW (480VAC)	40kW (480VAC)
Rated Current	155A per stack	220A 75 cell stack
Stack Count	3	1
Hydrogen Production	13 kg/day	13 kg/day
System Efficiency at Rated Current	75.6 (kWh/kg)	95.7 (kWh/kg)

Source: Eichman, J.D.; Harrison, K.; Peters, M. (Forthcoming). Novel Electrolyzer Applications. NREL/TP-5400-61758

Electrolyzer Response Time

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

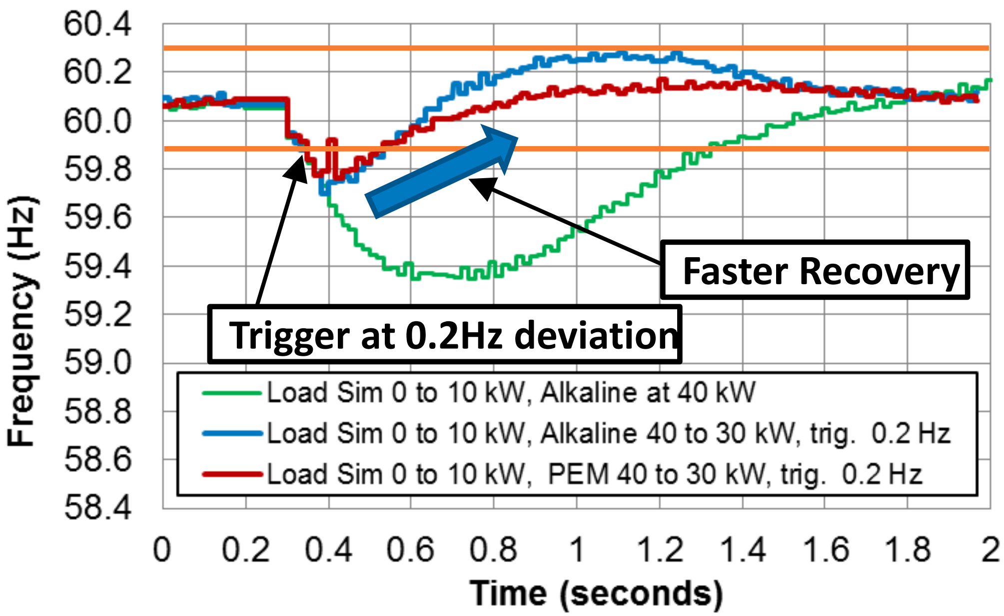




Electrolyzers can rapidly change their load point in response to grid needs

Electrolyzer Frequency Regulation Tests

- Tested frequency response using a microgrid

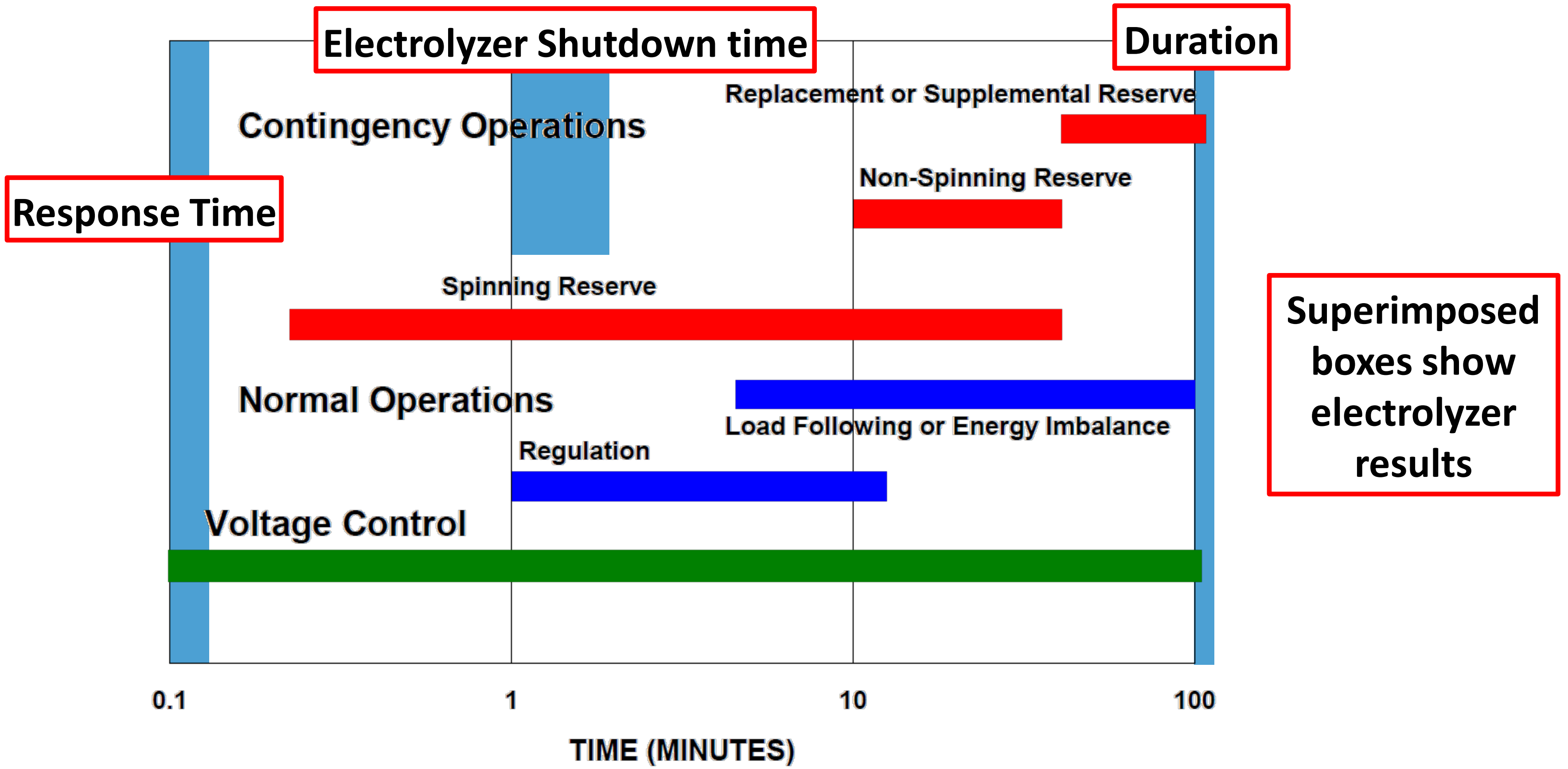


Source: Harrison K., Mann M., Terlip D., and Peters M., NREL/FS-5600-54658

Electrolyzers can accelerate frequency recovery

Electrolyzer Testing Results vs. Requirements

- **Grid Service Requirements**



Source: Kirby, B.J. 2006. Demand Response for Power Systems Reliability: FAQ. ORNL

Source: Eichman, J.D.; Harrison, K.; Peters, M. (Forthcoming). Novel Electrolyzer Applications. NREL/TP-5400-61758

Electrolyzers can respond fast enough and for sufficient duration to participate in electricity markets

Capacity req. for grid services is reducing

- **Minimum capacity requirements to bid into market**
  - 50 MW for E.ON as of 2006 [2]
  - 30 MW for EnBW, RWE, and VET for minute reserve power in Germany as of 2006 [2]
  - 10 MW for ISO-NE and the primary and secondary control markets in Germany [2, 4]
  - 1 MW for NYISO, PJM and CAISO [3, 4]
  - 100 kW load reduction in the case of NYISO curtailment program [1]
- **Capacity can often be aggregated**

1. NYISO Auxiliary Market Operations (2013). Emergency Demand Response Program Manual, New York Independent System Operator, http://www.nyiso.com/public/webdocs/markets_operations/documents/Manuals_and_Guides/Manuals/Operations/edrp_mnl.pdf.
2. Riedel, S. and H. Weigt Electricity Markets Working Papers: German Electricity Reserve Markets, Dresden University of Technology and Energy Economics and Public Sector Management, WP-EM-20, http://hannesweigt.de/paper/wp_em_20_riedel_weigt_Germany_reserve_markets.pdf.
3. Intelligent Energy Europe (2008). Market Access for Smaller Size Intelligent Electricity Generation (MASSIG): Market potentials, trends and marketing options for Distributed Generation in Europe, Energy Economics Group, Fraunhofer ISE, Technical University of Lodz, The University of Manchester and EMD International A/S, http://www.iee-massig.eu/papers_public/MASSIG_Deliverable2.1_Market_Potentials_and_Trends.pdf.
4. Cutter, E., L. Alagappan and S. Price (2009). Impacts of Market Rules on Energy Storage Economics, Energy and Environmental Economics, http://www.usaee.org/usaee2009/submissions/OnlineProceedings/8025-Energy%20Storage_Paper%20E3.pdf

Grid capacity requirements are approaching electrolyzer manufacturer scale-up targets

Modeling Approach

- **Modeling Strategies**
  - Price-taker
  - Production Cost
  - Hybrid

Can perform time-resolved co-optimization of energy and ancillary service products very quickly

<u>Historical or Modelled</u>

- Energy Prices
- Reserve Prices
- Hydrogen Price
- Operational parameters

Price-Taker

Profit based on operation (arbitrage, AS, H_2 sale, etc.)

Assumes

1.) Sufficient capacity is available in all markets

2.) Objects don't impact market outcome (i.e., small compared to market size)

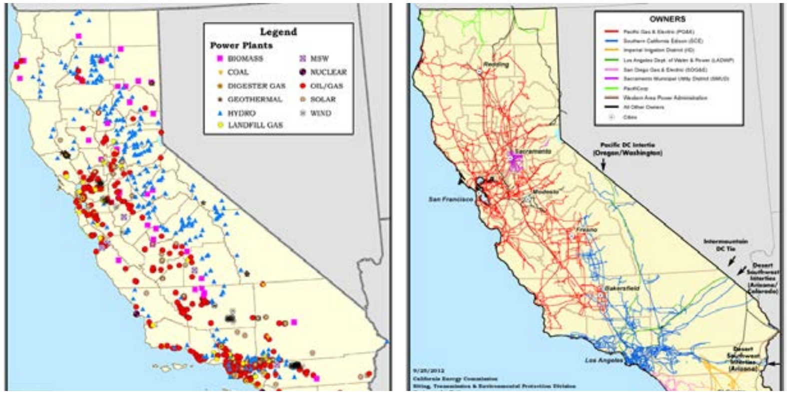
Modeling Approach: Production Cost Model

- Transmission Network (electric and gas)
- Generator properties
  (coal, gas, nuclear, renewable, etc.)
- Load requirements
- Reliability requirements
- Other System Constraints

For more details see Backup slides or Eichman J., 2014 DOE Annual Merit Review Presentation

Production Cost Model

- Generator operation
  (starts, fuel, costs)
- Fuel use and cost
- Emissions
- Transmission operation
  (flow, congestion)
- Imports & Exports
- Load served
- Energy Prices
- Reserve Prices



California Power Plants and Transmission Lines (energyalmanac.ca.gov/)

Performs co-optimization of energy and ancillary service products to minimize system production cost (days or weeks of runtime)

Modeling Approach: Hybrid

For more details see Backup slides or Eichman J., 2014 DOE Annual Merit Review Presentation

- Transmission Network (electric and gas)
- Generator properties (coal, gas, nuclear, renewable, etc.)
- Load requirements
- Reliability requirements
- Other System Constraints

Production Cost Model

- Generator operation (starts, fuel, costs)
- Fuel use and cost
- Emissions
- Transmission operation (flow, congestion)
- Imports & Exports
- Load served

- Energy Prices
- Reserve Prices
- Hydrogen Price
- Operational parameters

Price-Taker

Profit based on operation (arbitrage, AS, H_2 sale, etc.)

Models can be integrated (e.g., effect of renewables, changes to gas system, market design)

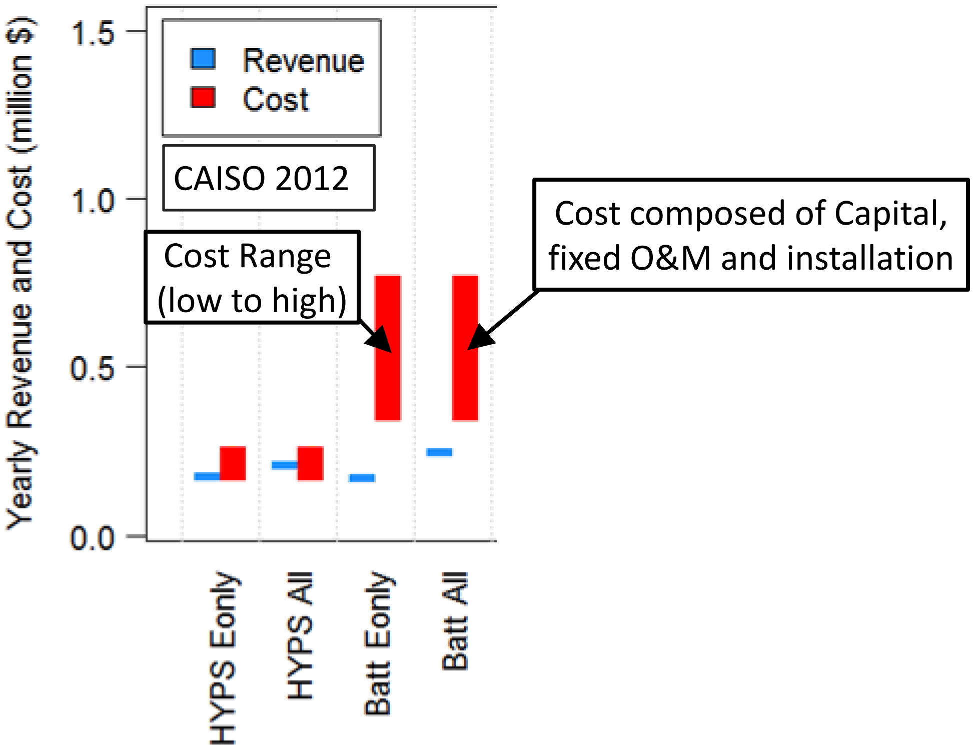
Approach – Assumptions for Price-taker

Properties	Pumped Hydro	Pb Acid Battery	Stationary Fuel Cell	Electrolyzer	Steam Methane Reformer
Rated Power Capacity (MW)	1.0	1.0	1.0	1.0	500 kg/day
Energy Capacity (hours)	8	4	8	8	8
Capital Cost ($/kW)	1500[1] - 2347[2]	2000[1] - 4600[1]	1500[3] - 5918[2]	430[3] - 2121[6]	427 – 569 $/kg/day[4]
Fixed O&M ($/kW-year)	8[1] - 14.27[2]	25[1] - 50[1]	350[2]	42[4]	4.07 – 4.50 % of Capital[4]
Hydrogen Storage Cost ($/kg)	-	-	623[5]	623[5]	623[5]
Installation cost multiplier	1.2[4]	1.2[4]	1.2[4]	1.2[4]	1.92[4]
Lifetime (years)	30	12[1] (4400hrs)	20	20[4]	20[4]
Interest rate on debt	7%	7%	7%	7%	7%
Efficiency	80% AC/AC[1]	90% AC/AC[1]	40% LHV	70% LHV	0.156 MMBTU/kg[4] 0.6 kWh/kg[4]
Minimum Part-load	30%[7]	1%	10%	10%	100%

Source: [1]EPRI 2010, Electricity Energy Storage Technology Options, 1020676
[2]EIA 2012, Annual Energy Outlook
[3]DOE 2011, DOE Hydrogen and Fuel Cells Program Plan
[4]H2A Model version 3.0
[5]NREL 2009, NREL/TP-560-46719 (only purchase once if using FC&EY system)
[6]NREL 2008, NREL/TP-550-44103
[7]Levine, Jonah 2003, Michigan Technological University (MS Thesis)

Price-Taker Results with historical prices

- **Comparison of yearly revenue and cost**



Name	Technology
HYPS	Pumped Hydro
Batt	Battery
FC	Fuel Cell
EY	Electrolyzer
SMR	Steam Methane Reformer

Name	Services
All	All Ancillary Services
Eonly	Energy Arbitrage only
Baseload	"Flat" operation

Price-Taker Results with historical prices

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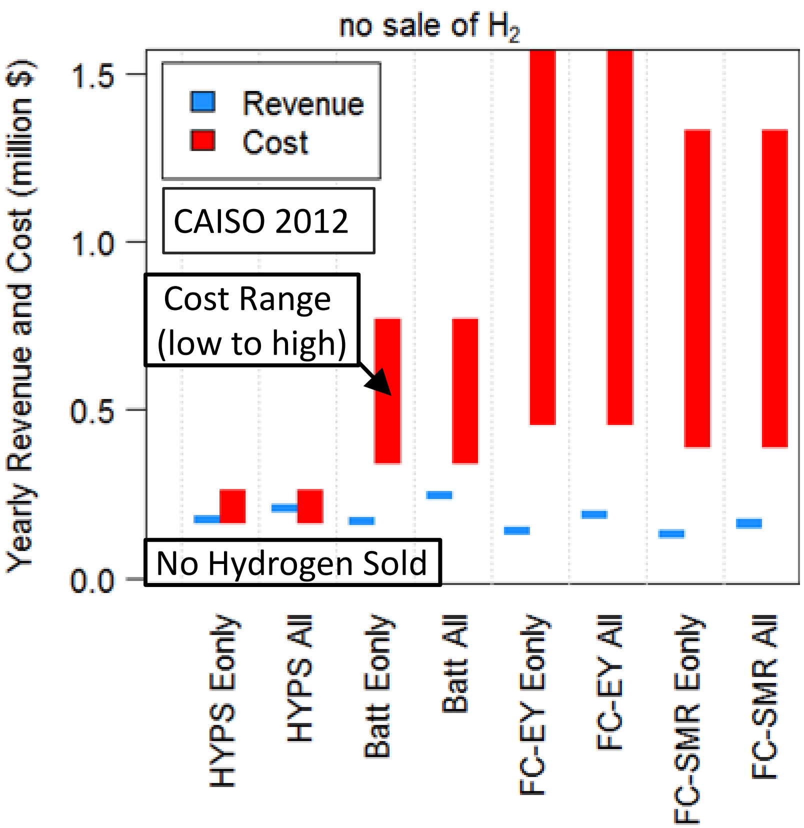

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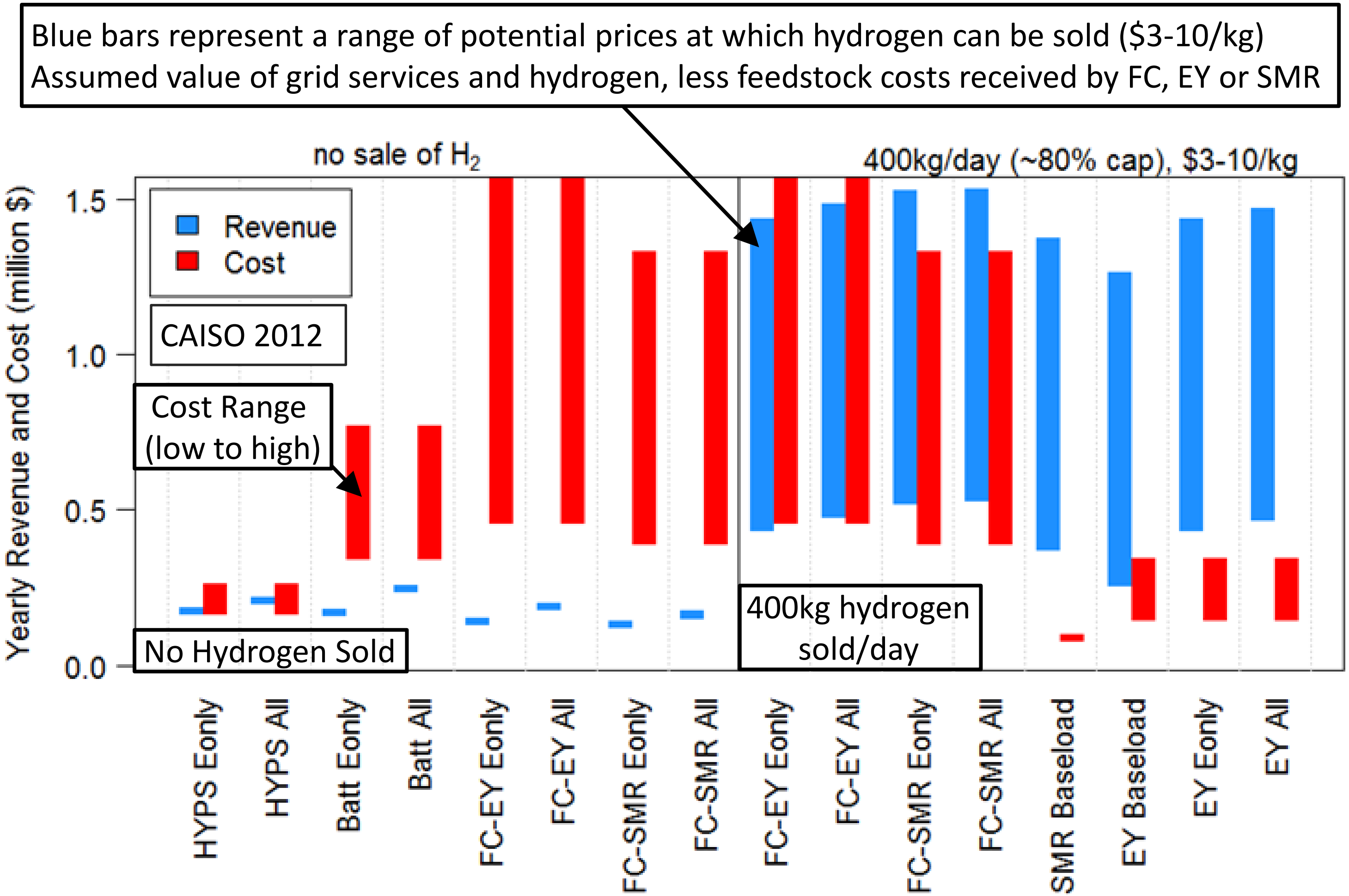
Price-Taker Results with historical prices

Selling hydrogen increases competitiveness

Providing ancillary services > Energy only > Baseload

Electrolyzer providing demand response is promising



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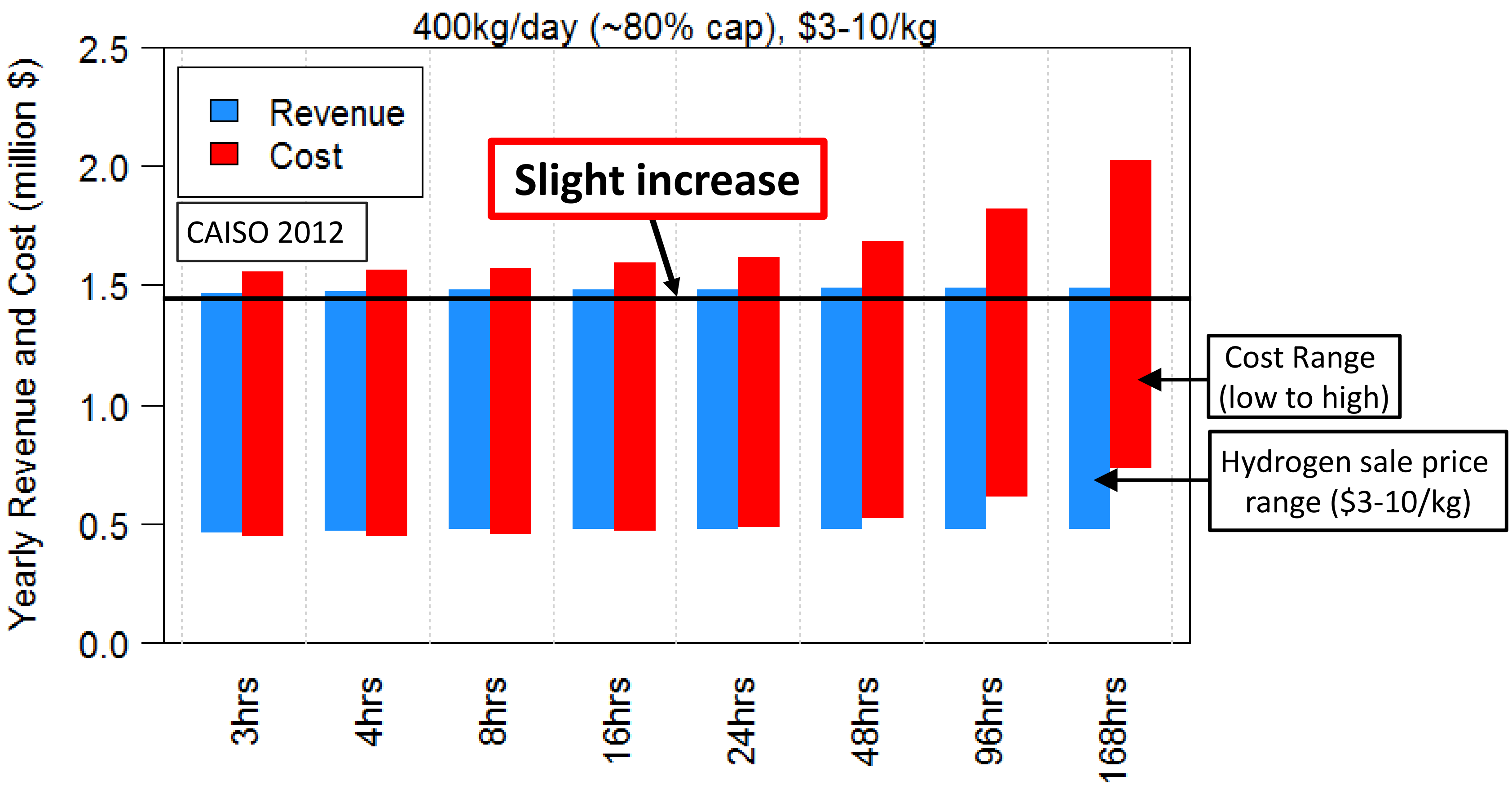
Energy Capacity Sensitivity Analysis

- **FC-EY storage device with varying energy capacity**



More storage is not necessarily more competitive in current energy and ancillary service markets

Hydrogen Energy Storage Workshop

Goal: Identify challenges, benefits and opportunities for commercial hydrogen energy storage applications to support grid services, variable electricity generation, and hydrogen vehicles

Scope: Convened by U.S. DOE and Industry Canada to explore a broad range of services from Hydrogen storage systems in the near and long term

Sheraton HOTELS & RESORTS

MAY 14-15TH, SACRAMENTO, CA

Focus: Four key topics:

- Lessons Learned and Demonstration Status
- Market Opportunities and Business Models
- Technology R&D and Near-Term Market Potential
- Policy and Regulatory Challenges and Opportunities

Workshop Participants

- **65 participants with a significant diversity of stakeholder types and a focus on policy expertise**

<u>California State Government Agencies</u>

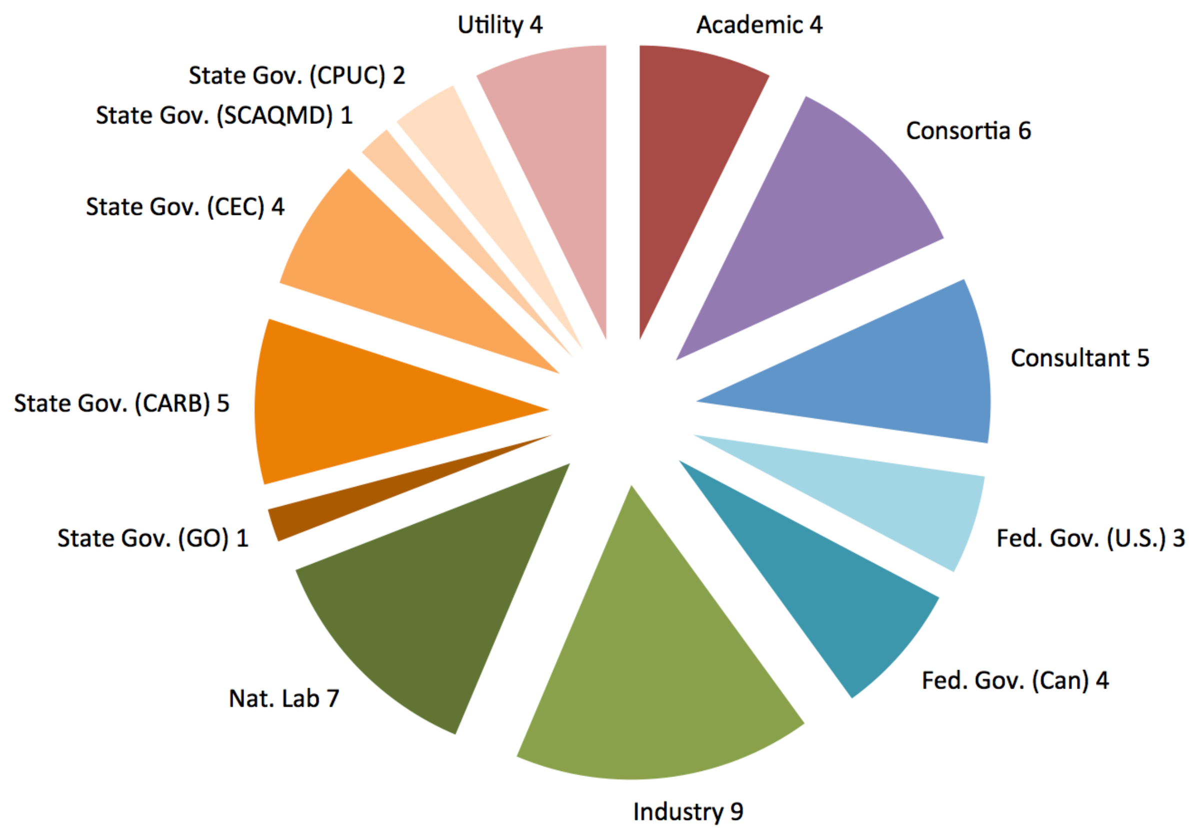
CPUC: California Public Utilities Commission

SCAQMD: South Coast Air Quality Management District

CEC: California Energy Commission

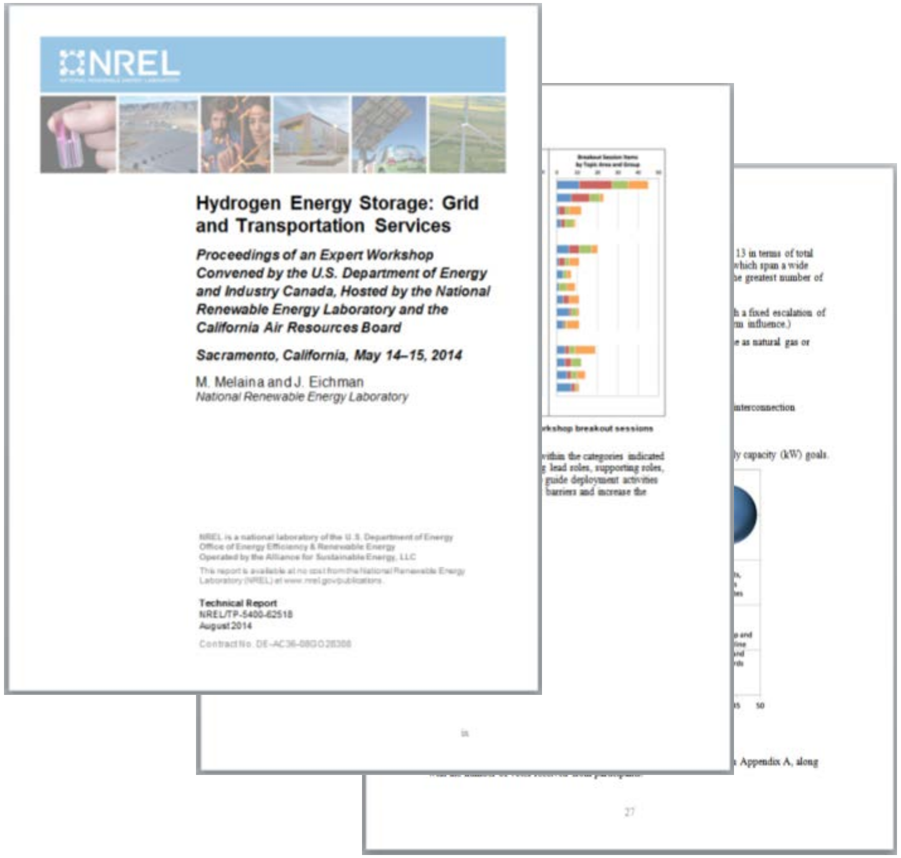
CARB: California Air Resources Board

GO: Governor's Office



Preliminary Workshop Findings

- **Example Findings**
  - Criteria and Barriers
    - Technical and Economic Viability
    - Multiple end uses
  - Policy
    - Equal treatment and credit in markets
  - Next Steps
    - Demonstration and pilot projects



Source: Melaina, M., J. Eichman, (In Review). "Hydrogen Energy Storage: Grid and Transportation Services". NREL/TP-5400-62518

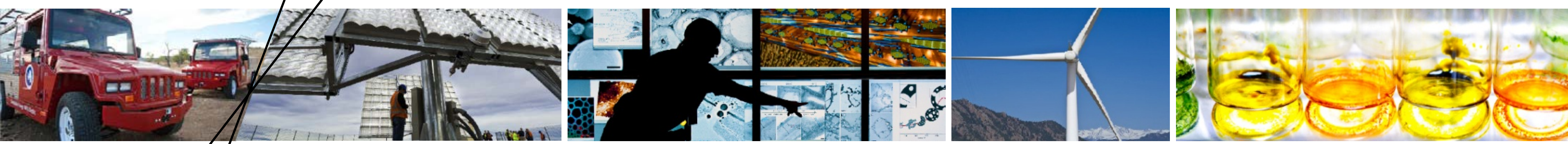
Analysis Conclusions

Flexibility

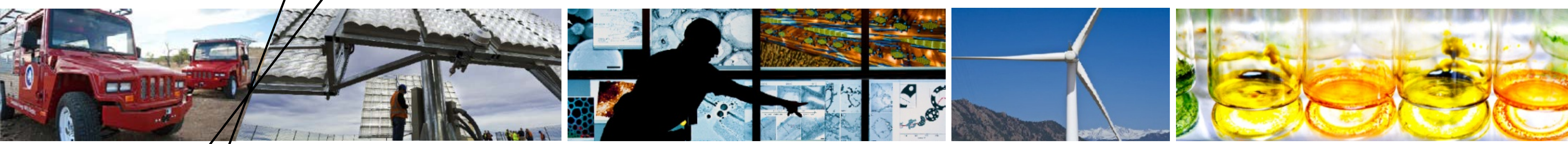
1. Electrolyzers can respond sufficiently fast and for a long enough duration to participate in electricity markets.

Economic Viability

1. Sell Hydrogen: Systems providing strictly storage are less competitive than systems that sell hydrogen
2. Revenue w/ ancillary service > energy only > baseload
3. Electrolyzers operating as a "demand response" devices have very favorable prospects
4. More storage is not necessarily more competitive in current energy and ancillary service markets



Questions?

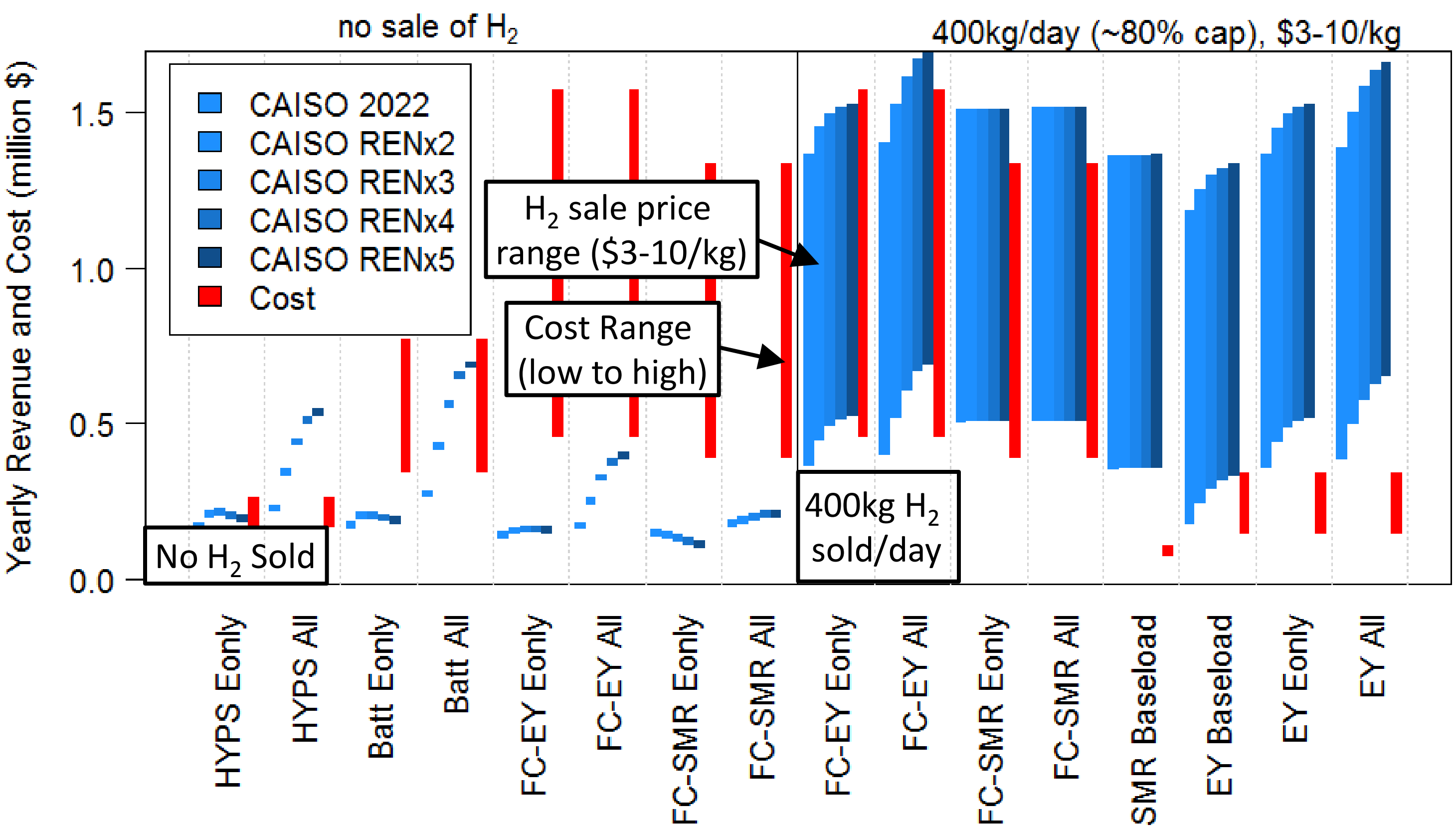


Backup Slides

Hybrid model results with high renewables

More Renewables yields greater value for hydrogen equipment

- **Projected renewable capacity in California in 2022 increased by 2x, 3x, 4x and 5x**



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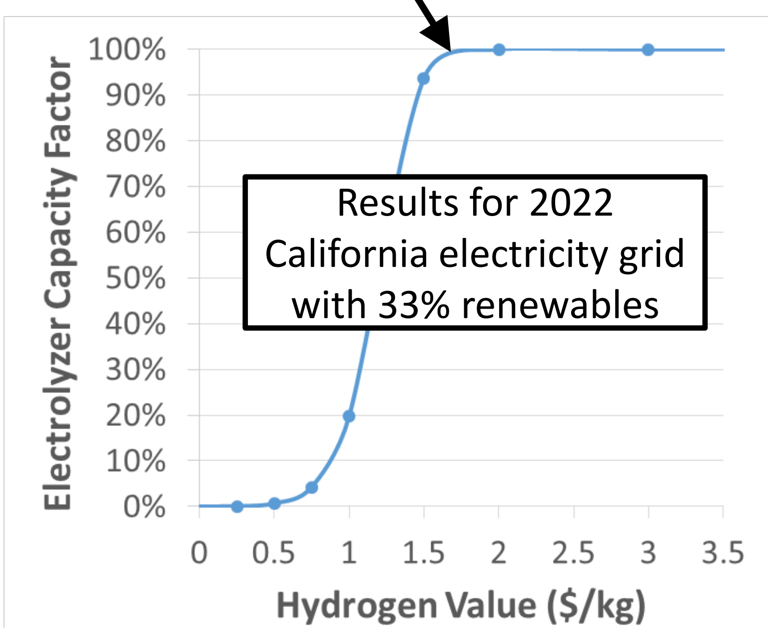
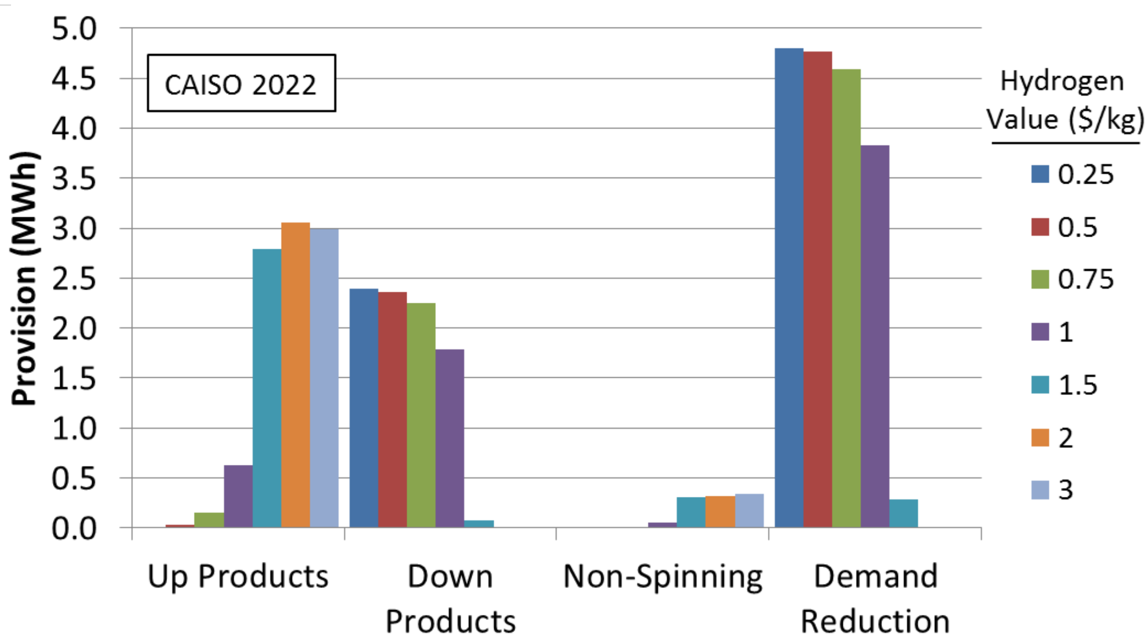
Production Cost Results for Electrolyzer acting as a demand response device

- **Integrating H_2 devices into a large-scale grid simulation tool shows how the grid will be affected**
  - Emissions
  - Production cost
  - Generation mixture
  - Prices

High value of H_2 makes it more valuable than elec. (incl. arbitrage and ancillary services)

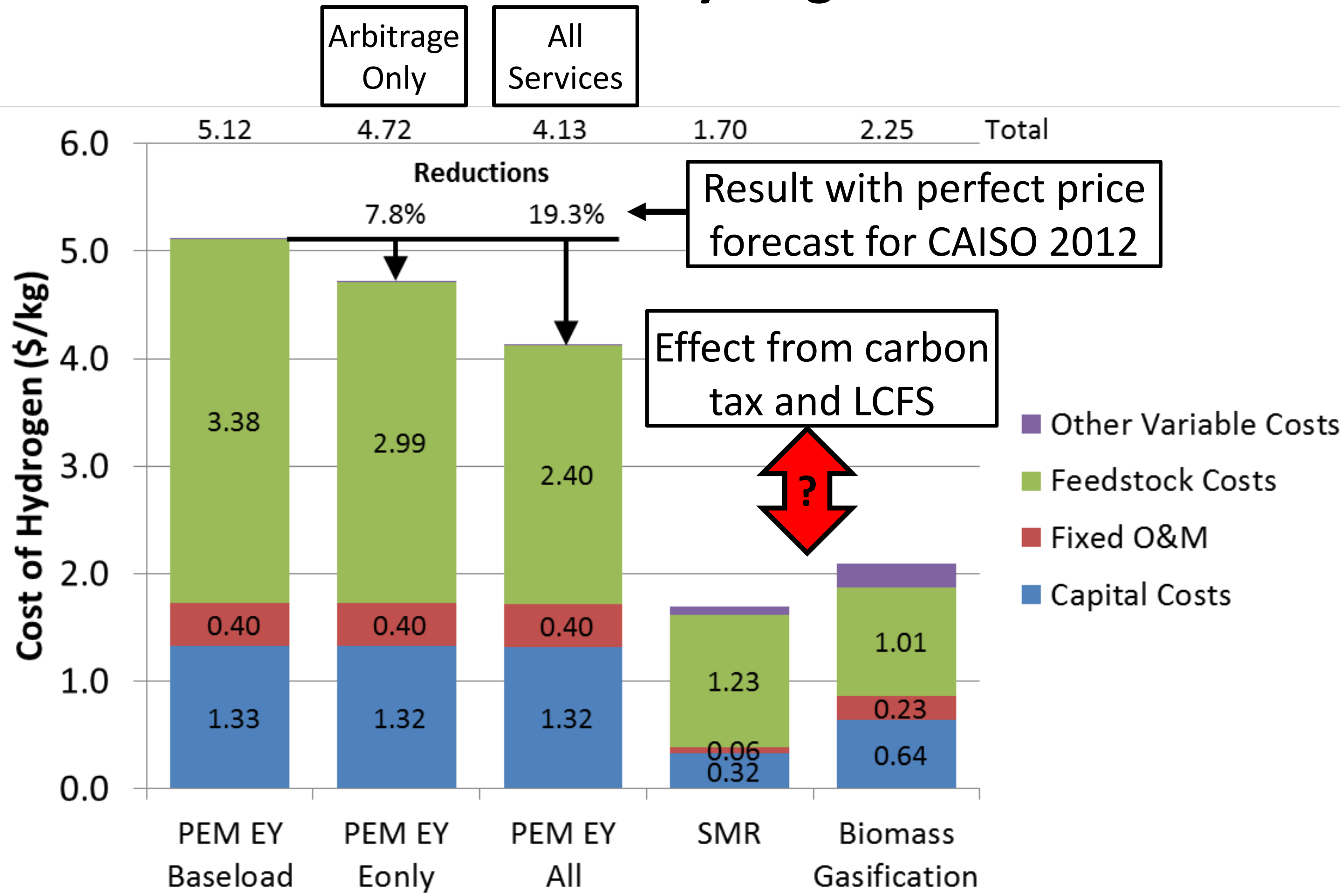




Comparison to H2A

Integration with the grid can lower feedstock costs and increase revenue

- **H2A Current Central Hydrogen Production**



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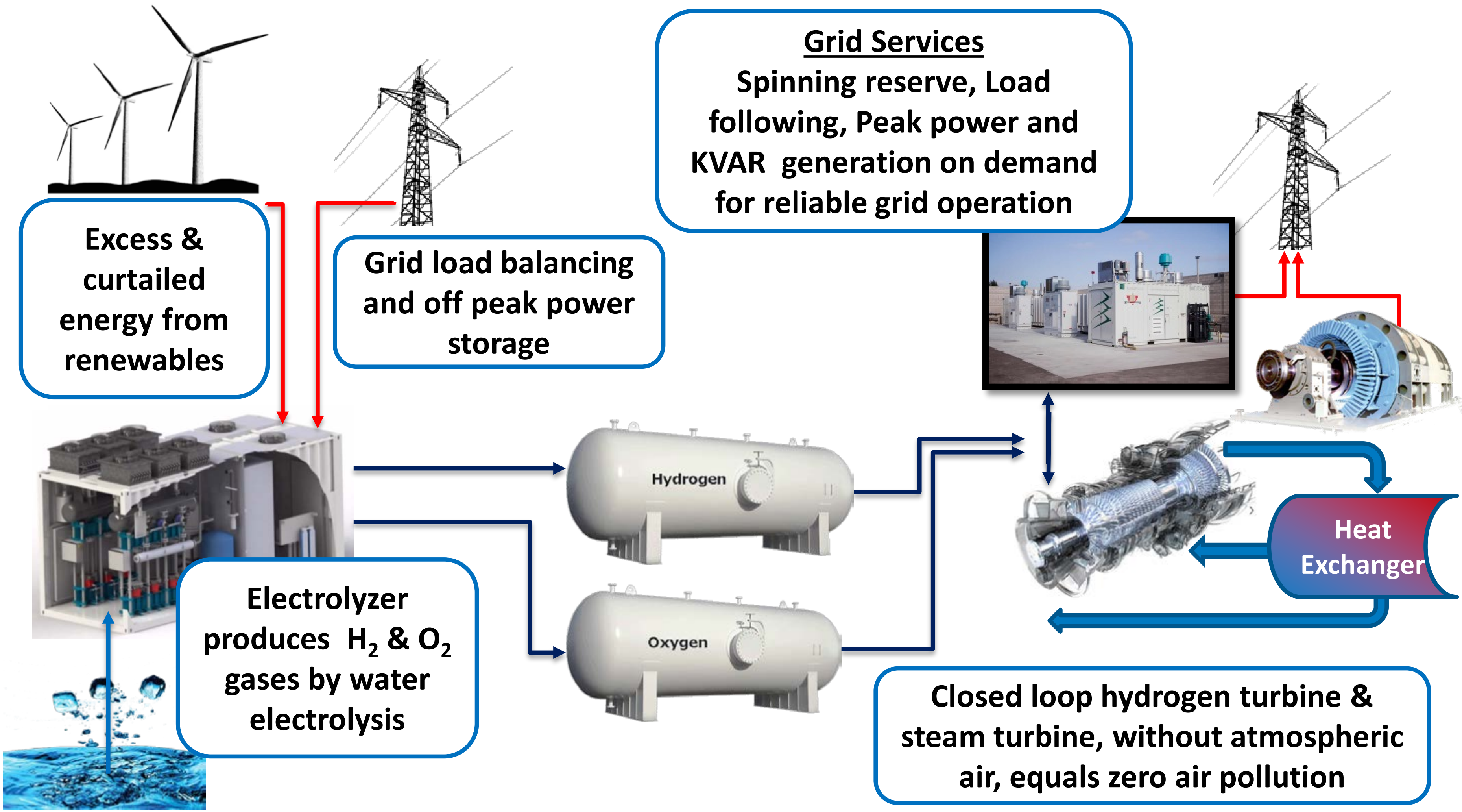
NREL and West Texas A&M University

Project to show how hydrogen technologies can be used to support grid operation and when high renewable penetrations require long-term storage



Thank You

Monterey.Gardiner@ee.doe.gov