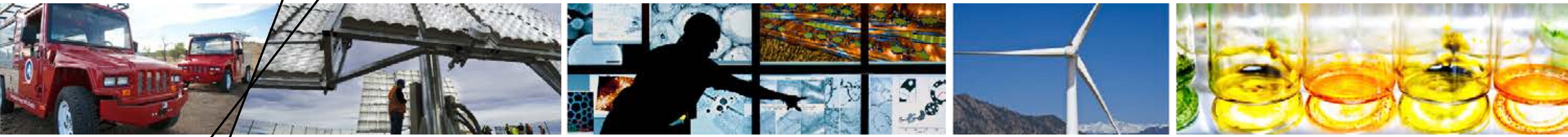
Hydrogen Energy Storage (HES) Activities at NREL



HTAC

Josh Eichman, PhD

Hydrogen and Fuel Cell Technical Advisory Committee Meeting

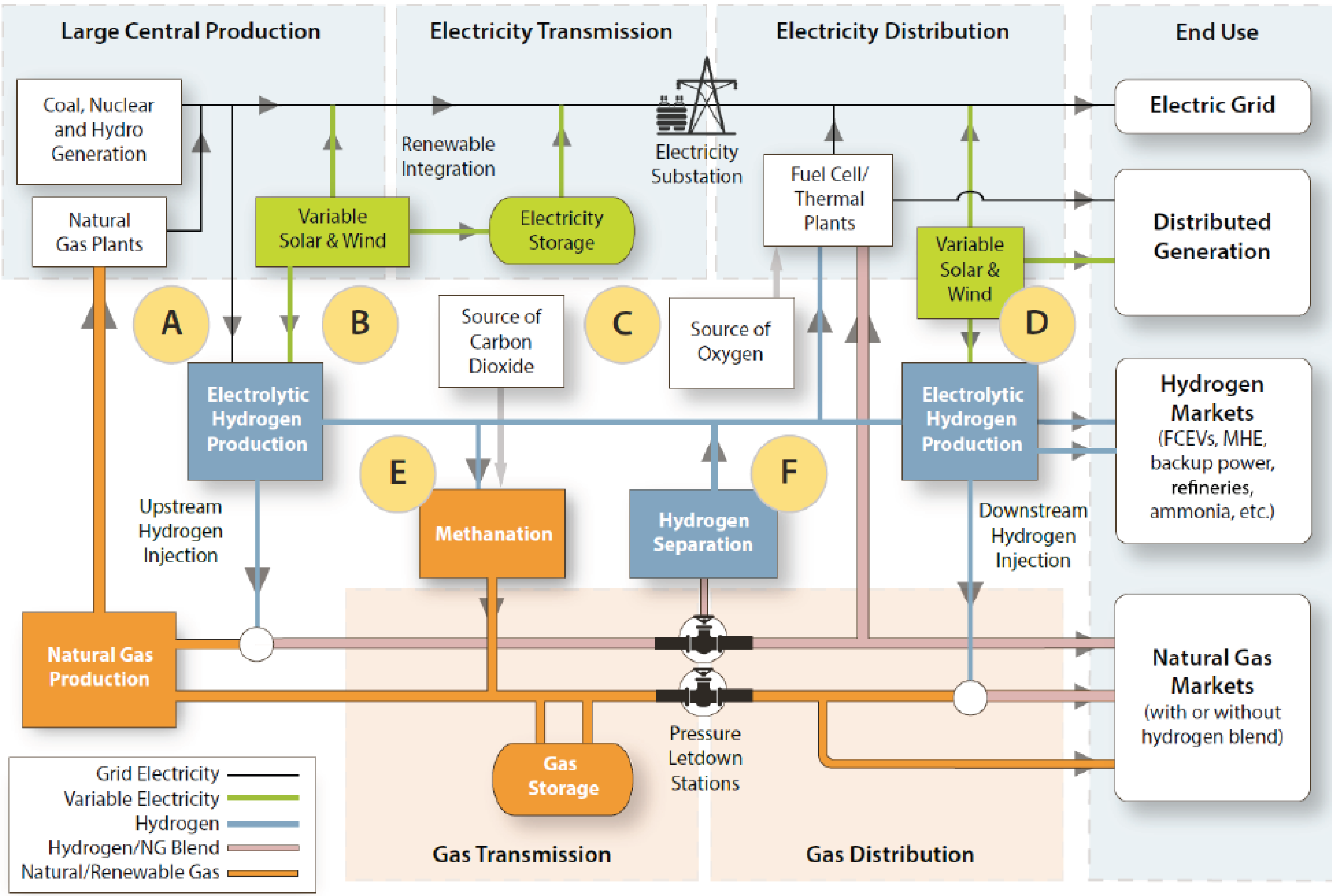
4/21/2015

NREL/PR-5400-64137
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Outline

- **Hydrogen and Energy Storage Overview**
  - Hydrogen storage pathways
  - International Power-to-gas activities
- **Hydrogen energy storage activities**
  - NREL – DOE storage analysis results (FY14)
  - NREL – DOE storage analysis tasks (FY15)
  - Energy Storage Workshop results
  - Clean Energy Dialogue – US/Canada
- **Update: INTEGRATE activities**
- **Newly Proposed CARB-DOE Project**
- **NREL – SoCalGas Project**

Hydrogen energy storage pathways



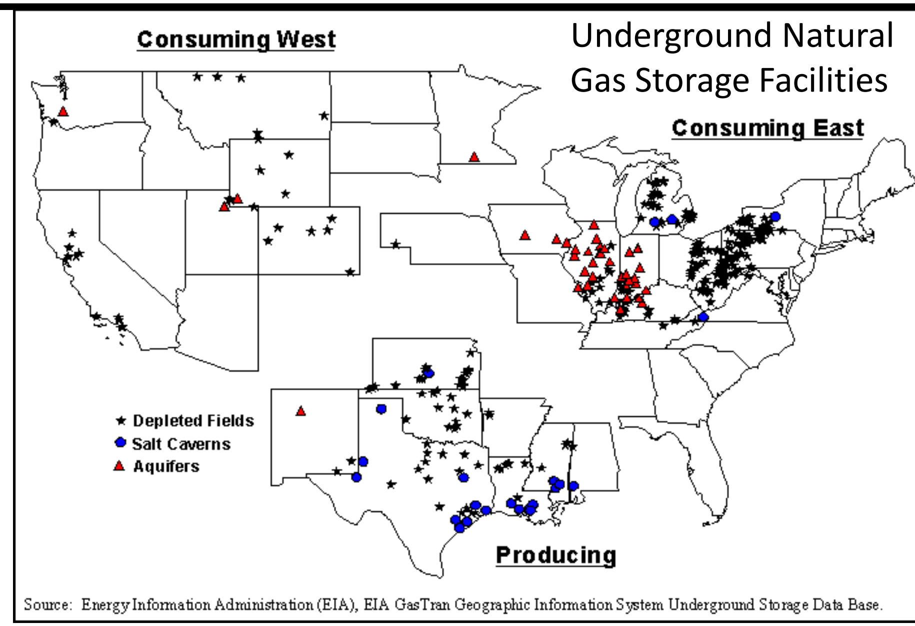
A. Electrolysis for Grid Support
B. Integration of large-scale central renewables
C. Conversion to grid electricity
D. Distributed production for variable resources
E. Methanation for renewable gas synthesis
F. Hydrogen Separation

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

Opportunities for Power-to-gas

- **Natural Gas System**
  - 305,000 miles of transmission pipelines
  - 400 underground natural gas storage facilities
  - 3.9 Bcf underground storage working gas capacity

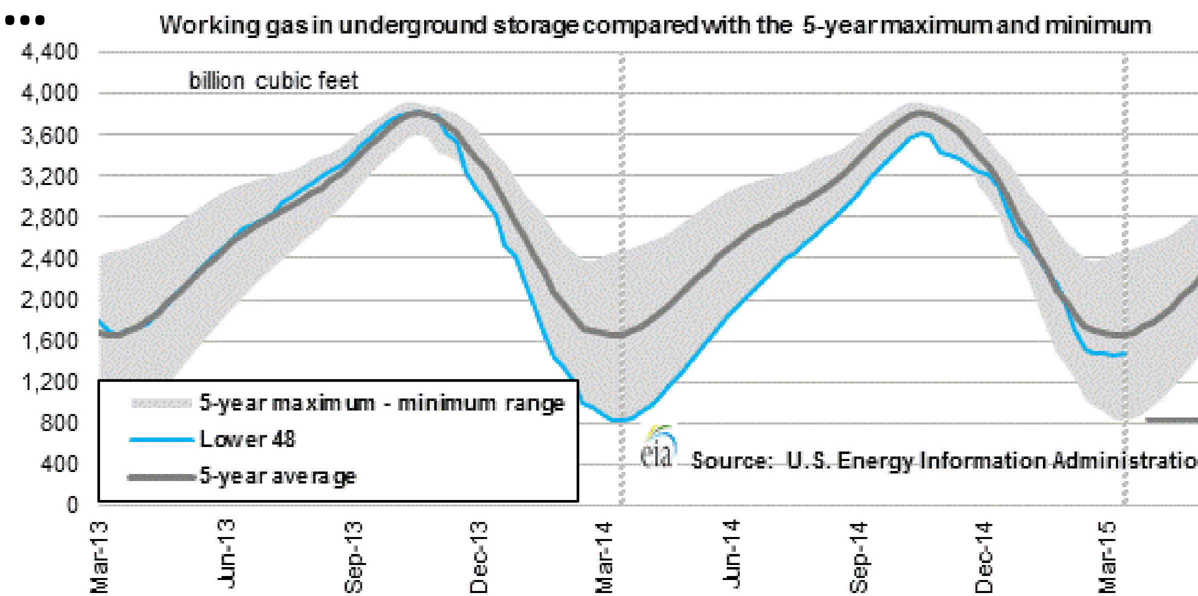
Source: www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/index.html



- **Storage equates to…**
  - 38 billion kg of H_2 used to produce CH_4 from CO_2 methanation for one fill

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

(Sabatier process)



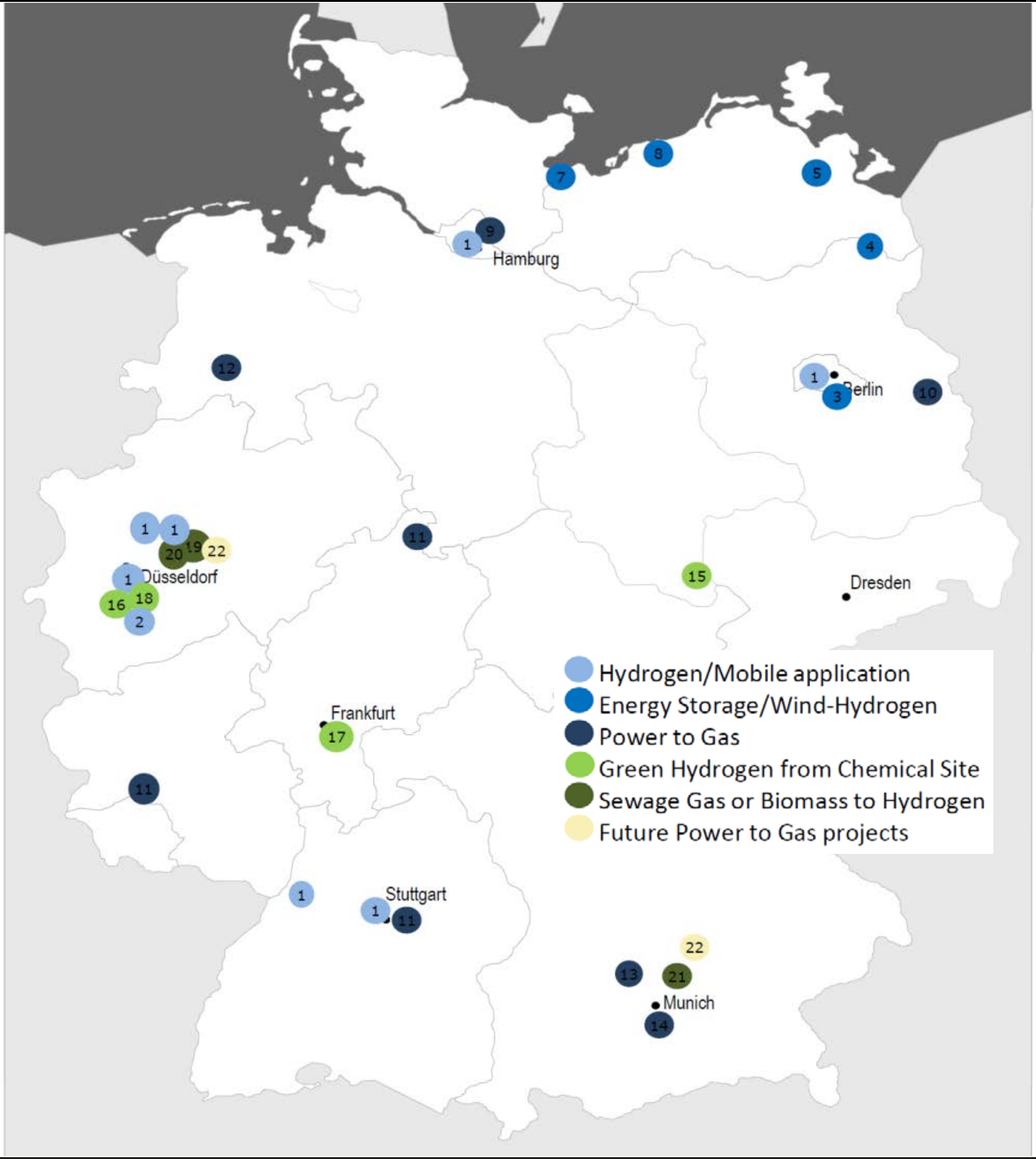
Hydrogen storage and Power-to-gas (PtG) projects

- **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

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

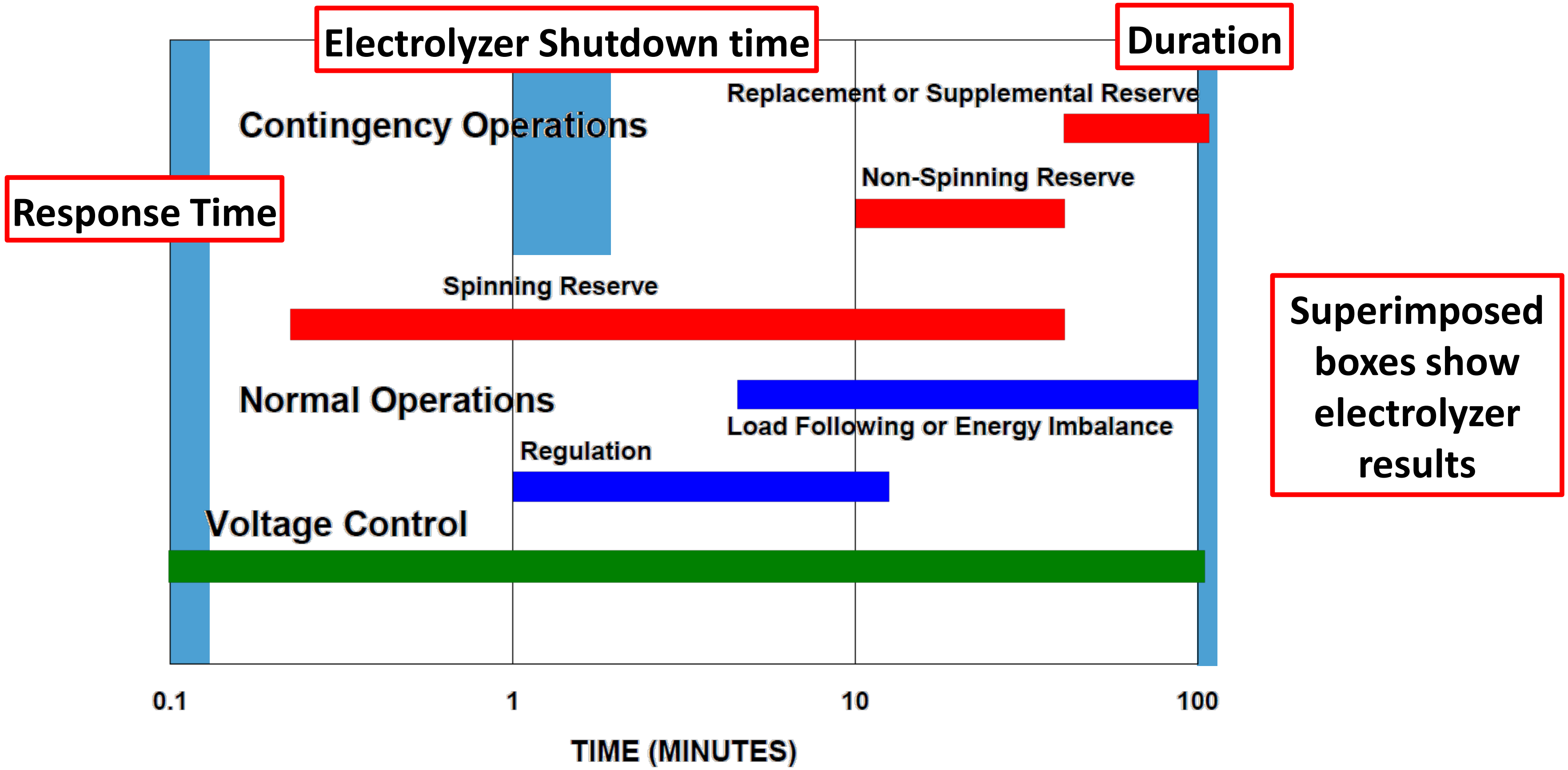
Source: www.hydrogenics.com/about-the-company/news-updates/2014/07/25/hydrogenics-selected-for-2-megawatt-energy-storage-facility-in-ontario



NREL – DOE storage analysis activities for FY14

Electrolyzers can respond fast enough and for sufficient duration to participate in electricity markets (need to test large electrolyzers)

- **Compared PEM and Alkaline Electrolyzer response to grid requirements**



Source: Kirby, B.J. 2006. Demand Response for Power Systems Reliability: FAQ. ORNL/TM-2006/565

Source: Eichman, J.; Harrison, K.; Peters, M. (2014). Novel Electrolyzer Applications: Providing more than just hydrogen, NREL/TP-5400-61758, http://www.nrel.gov/docs/fy14osti/61758.pdf

Quantify the value of energy storage

An operations optimization model is used to quantify value from electricity markets and the sale of hydrogen

- **Optimization model can perform time-resolved co-optimization of energy, ancillary service and hydrogen products very quickly**
- **Assumptions**
  - Sufficient capacity is available in all markets
  - Objects don't impact market outcome (i.e., small compared to market size)

Historical or Modelled

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

Optimization model

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

Approach – Assumptions for Price-taker

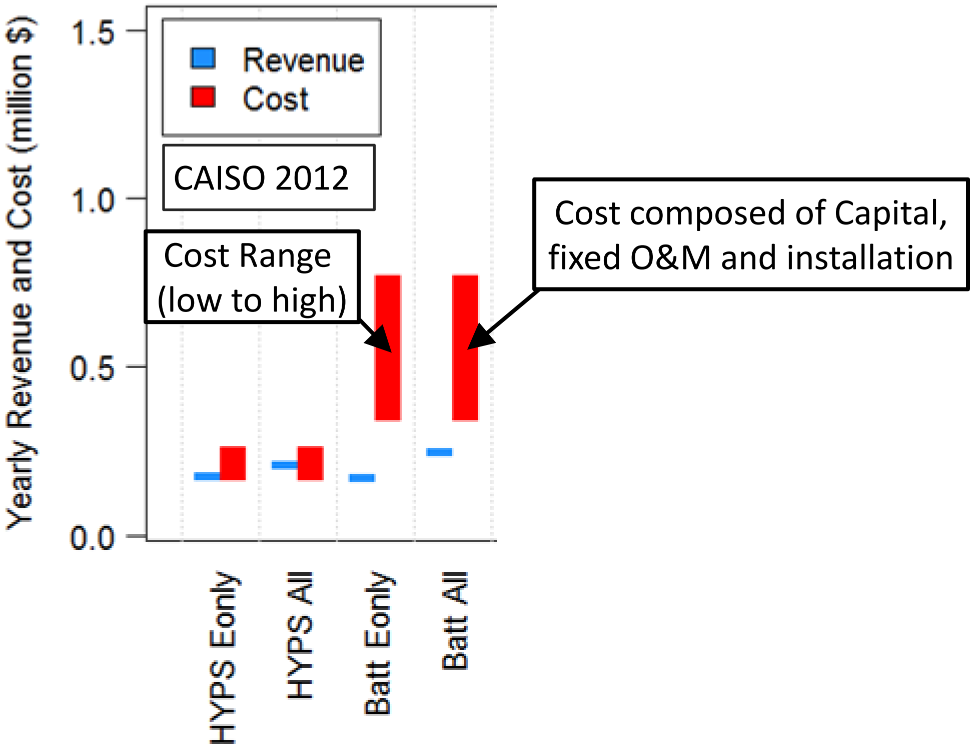
Properties	Pumped Hydro	Pb Acid Battery	Stationary Fuel Cell	Electrolyzer	Steam Methane Reformer
Rated Power Capacity (MW)	1.0	1.0	1.0	1.0	500 kg/day
Energy Capacity (hours)	8	4	8	8	8
Capital Cost ($/kW)	1500[1] - 2347[2]	2000[1] - 4600[1]	1500[3] - 5918[2]	430[3] - 2121[6]	427 – 569 $/kg/day[4]
Fixed O&M ($/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

Conventional storage technologies are often not competitive based on direct market revenue

- **Comparison of yearly revenue and cost**



Yearly Revenue ($M)	0.18	0.22	0.18	0.26
Yearly Cost ($M)	0.16-0.26	0.16-0.26	0.34-0.77	0.34-0.77

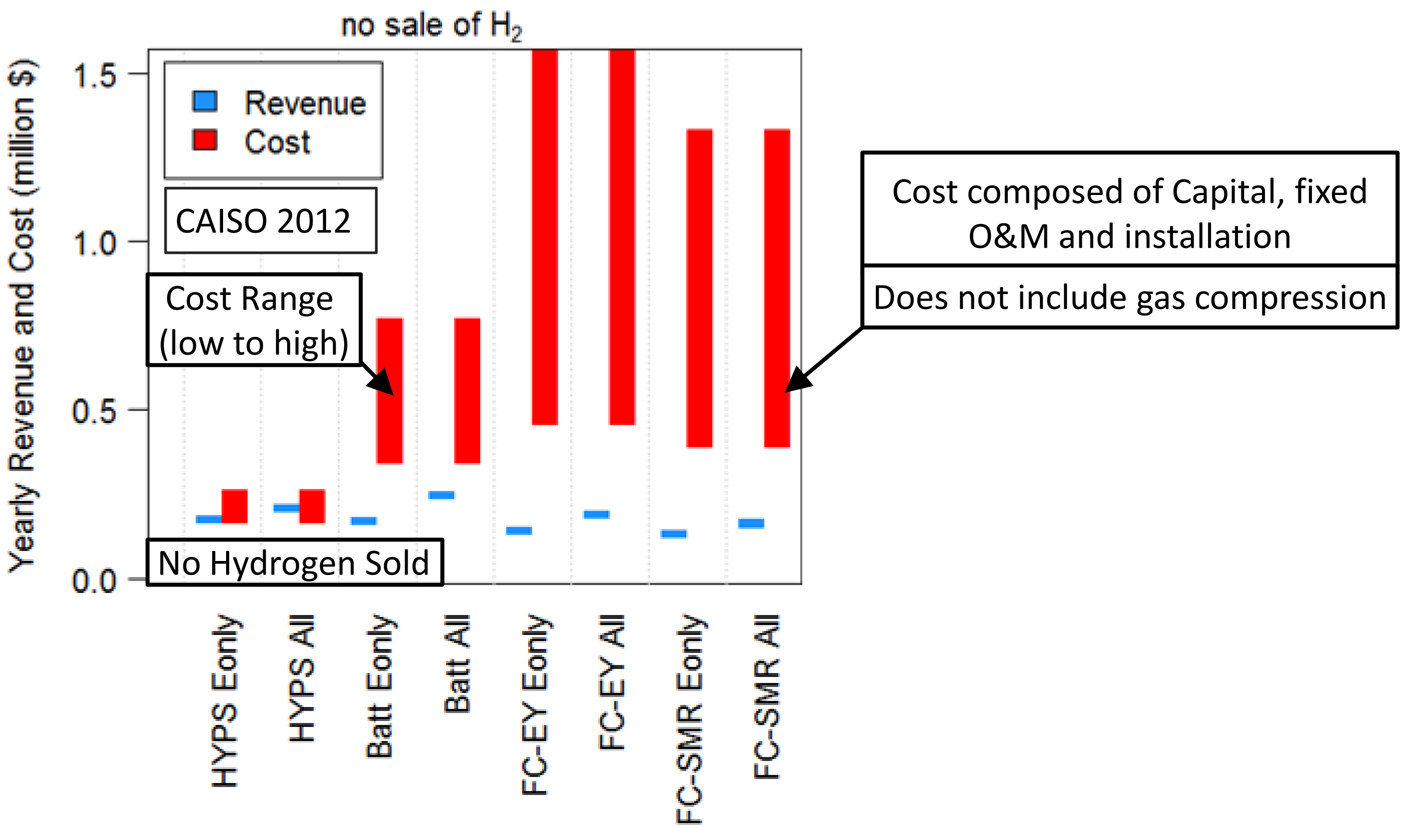
Name	Technology
HYPS	Pumped Hydro
Batt	Battery
FC	Fuel Cell
EY	Electrolyzer
SMR	Steam Methane Reformer

Name	Services
All	All Ancillary Services
Eonly	Energy Arbitrage only
Baseload	“Flat” operation

Price-Taker Results with historical prices

For electricity-in, electricity-out storage, fuel cell system costs must be reduced to improve competitiveness

- **Comparison of yearly revenue and cost**



Yearly Revenue ($M)	0.18	0.22	0.18	0.26	0.15	0.20	0.14	0.17
Yearly Cost ($M)	0.16-0.26	0.16-0.26	0.34-0.77	0.34-0.77	0.45-1.57	0.45-1.57	0.39-1.33	0.39-1.33

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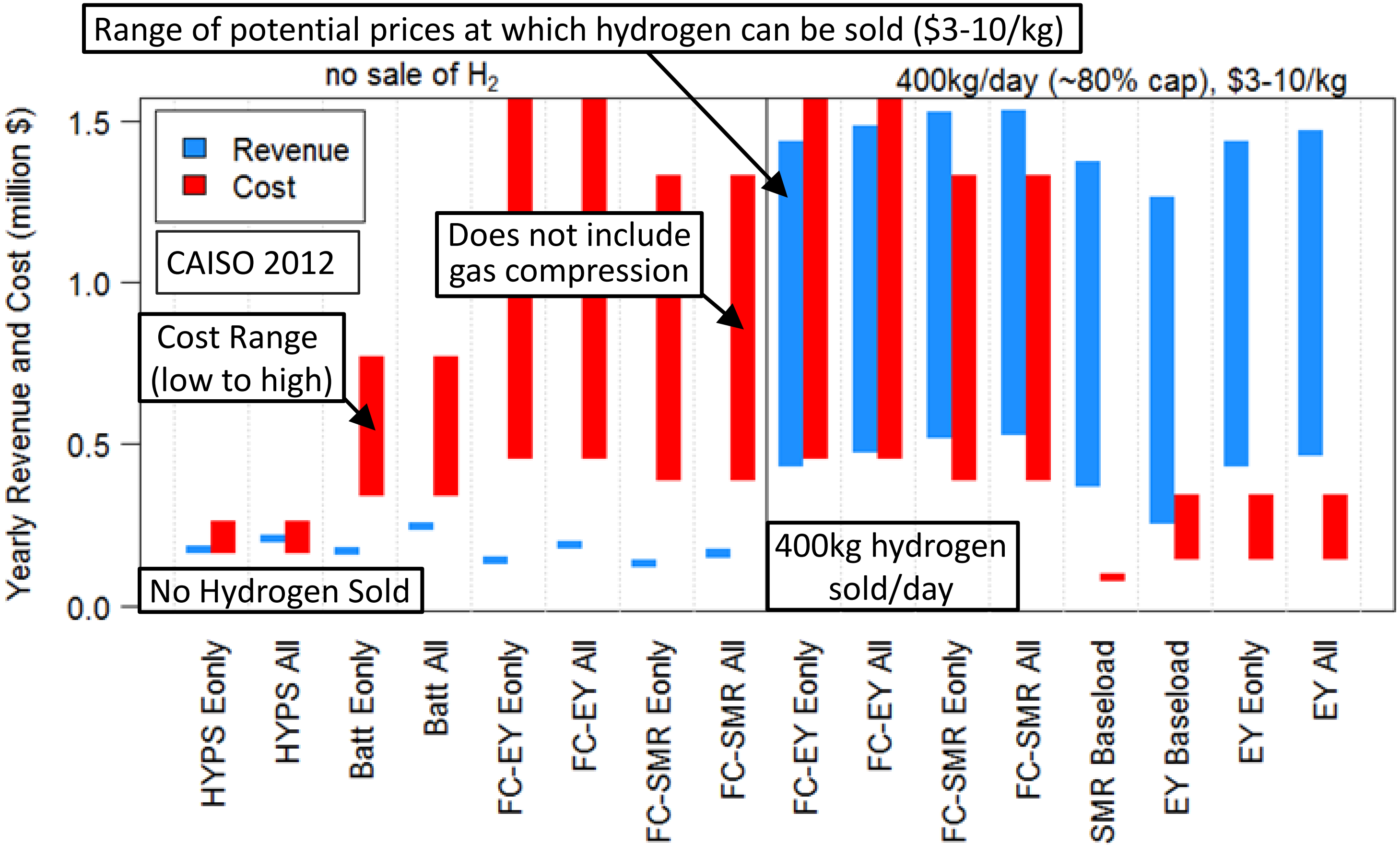
Price-Taker Results with historical prices

Selling hydrogen increases competitiveness

Providing ancillary services > Energy only > Baseload

Electrolyzers providing demand response are promising



	HYPS Eonly	HYPS All	Batt Eonly	Batt All	FC-EY Eonly	FC-EY All	FC-SMR Eonly	FC-SMR All	FC-EY Eonly	FC-EY All	FC-SMR Eonly	FC-SMR All	SMR Baseload	EY Baseload	EY Eonly	EY All
Yearly Revenue ($M)	0.18	0.22	0.18	0.26	0.15	0.20	0.14	0.17	0.43-1.44	0.47-1.48	0.52-1.53	0.53-1.53	0.37-1.38	0.25-1.26	0.43-1.44	0.46-1.47
Yearly Cost ($M)	0.16-0.26	0.16-0.26	0.34-0.77	0.34-0.77	0.45-1.57	0.45-1.57	0.39-1.33	0.39-1.33	0.45-1.57	0.45-1.57	0.39-1.33	0.39-1.33	0.08-0.1	0.14-0.34	0.14-0.34	0.14-0.34

Name	Technology
HYPS	Pumped Hydro
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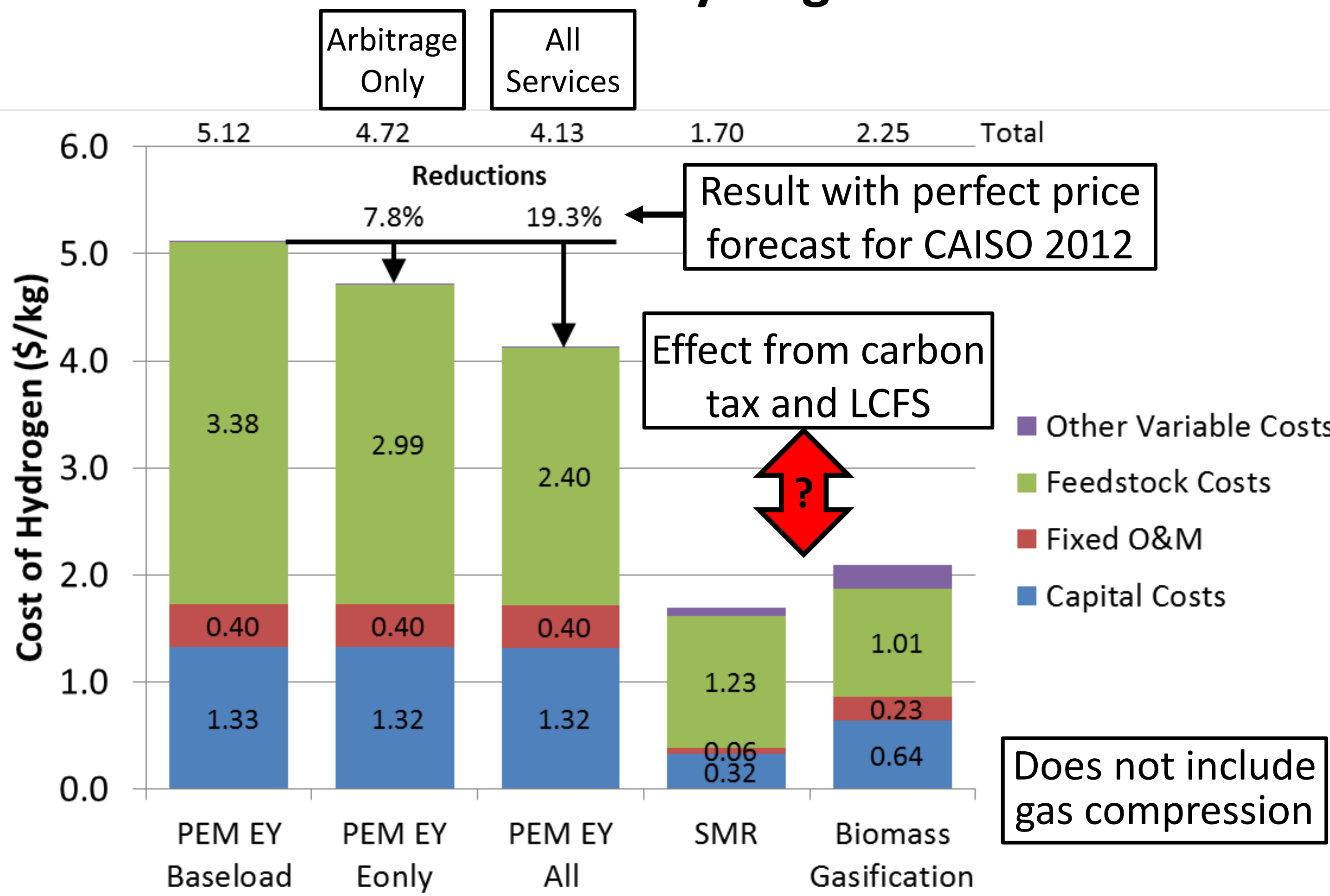
Baseload	“Flat” operation

Comparison of H2 Produced from Energy Storage to Dedicated H2 Production Units

Integration with the grid can lower feedstock costs and increase revenue

- **H2A Current Central Hydrogen Production**



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Name	Services
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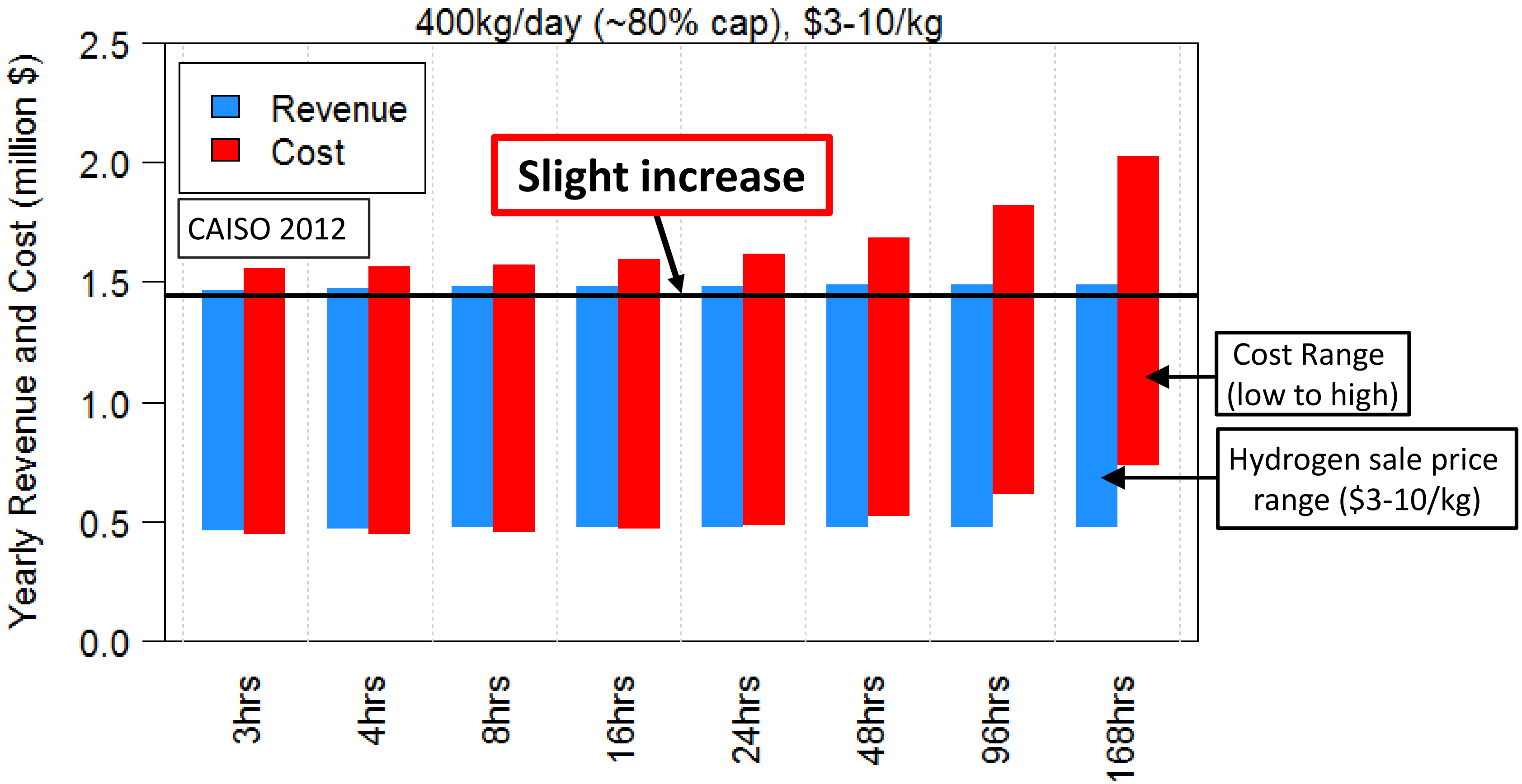
Baseload	"Flat" operation

Energy Capacity Sensitivity Analysis

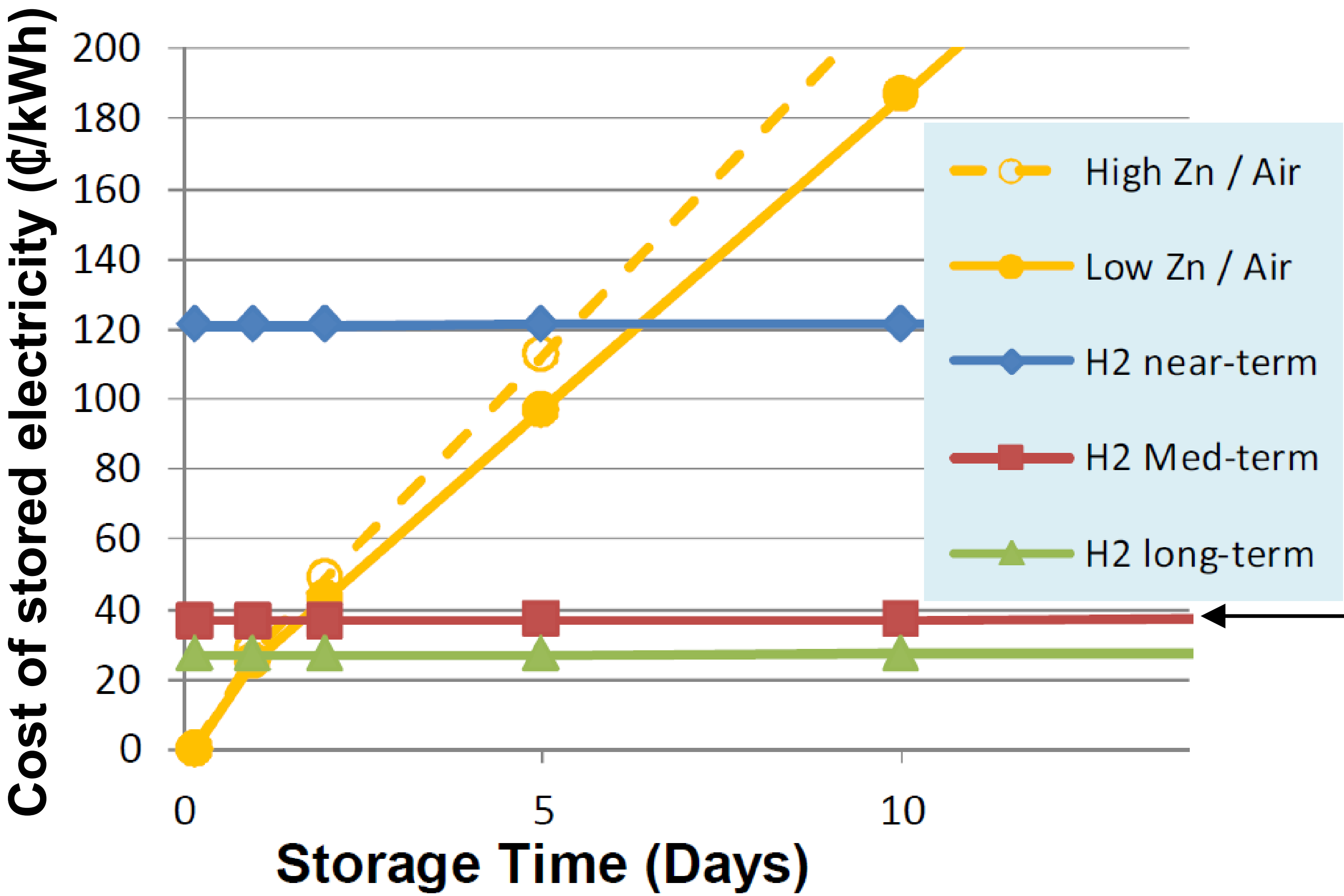
More storage is not necessarily more competitive in current energy and ancillary service markets

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



HTAC simple model for comparison

HTAC simple model and current modeling results are in agreement
Both show reduced value for additional storage



Assumptions
10MW output
6¢/kWh electricity
10% free energy
4hrs/day discharging
8hrs/day charging

Notice the cost of stored electricity rises slightly

Electrolytic Hydrogen Production Workshop Results (NREL 2/2014)

- **Commercial Technology Internal Challenges**
  - Improved **stack performance**
  - Increase **stack size** to at least 1 MW.
  - **High-pressure** stack/system/components to eliminate at least one stage of mechanical compression at 700-bar.
  - **Market issues**
  - **Grid integration**

- **Pre-commercial Technologies Internal Challenges**
  - Increased understanding of **degradation mechanisms**, at high current densities and under cycling conditions
  - **Scale-up**: Large format cells
  - **Material durability**, prove endurance to less than 0.5% degradation per 1000 hours
  - **Characterization of material interactions** for low technology readiness level (TRL) technologies.
  - **Improved initial performance**, and efficiency, especially at high current density (cell performance)
  - High quality **thermal integration** for SOEC to heat source with low stack thermal gradients.

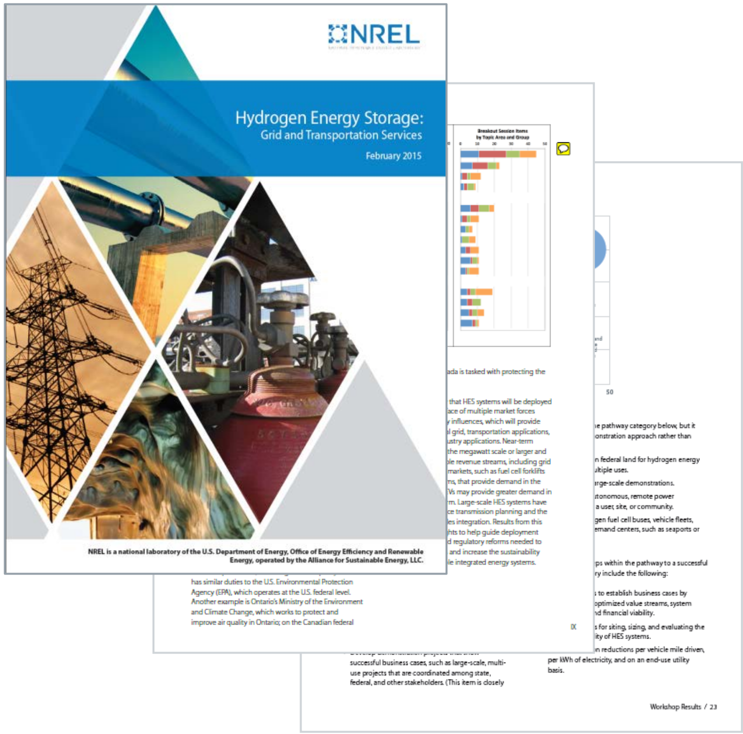
- **Additional Market Opportunities (ranked by order of votes)**
  1. Power to gas
  2. Ancillary grid services
  3. Renewable H_2 for petroleum refining
  4. Materials Handling Equipment

- **Manufacturing and Scale-up Challenges**
  1. Cost and limited availability of component and process validation
  2. Financial support
  3. Material purity/development
  4. Develop advanced manufacturing processes
  5. Design for Manufacture and Assembly (DFMA™) analysis for low volume
  6. Low-cost manufacturing development for low-volume market

Source: http://energy.gov/eere/fuelcells/downloads/electrolytic-hydrogen-production-workshop

Clean Energy Dialogue – US/Canada

- **Clean Energy Dialogue**
  - Launched on February 19, 2009
  - Enhance bilateral collaboration for clean energy science and technologies to reduce GHGs and combat climate change.
  - Support efforts to build a low-carbon North American economy
- **Hydrogen Energy Storage (HES) Workshop**
  - Held May, 2014 in Sacramento, CA and included a diversity of stakeholder types
  - Explored barriers, policy and next steps for encouraging HES
  - Workshop proceedings are available
- **Power-to-Gas project**
  - Understand geographic & environmental circumstance where power-to-gas makes sense
  - Simulate Power-to-gas systems
    - Scenario based approach
    - Simulate behavior, financial and possibly environmental performance
    - Canadian Nuclear Laboratories and National Research Council Canada working on Power-to-Gas standalone software module
    - EPRI working on integrating Hydrogen into a simplified version of energy storage valuation tool
    - NREL is supporting with some inputs and project review
  - This project is expected to conclude in August 2015.



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

NREL – DOE storage analysis activities for FY15

- **Follow-up Workshop**
  - Follow-up to May 2014 workshop to be held in Golden, CO at ESIF
  - Focus will be more on technical issues related to HES and Power-to-gas
- **Further quantify value of HES**
  - Expand data to multiple years and locations
  - Explicit spatial modeling (e.g., prices, infrastructure)
  - Incentive and credit opportunities
  - Quantify electricity market size

INTEGRATE – Electrolyzer Stack Test Bed and RTDS communication

- **Completed the design, installation and commissioning of a 250 kW stack test bed**
  - o AC/DC power supplies are capable of 500 kW (250V, 2000A)
    - – Presently limited due to component flow limitations
- **Successful data exchange from INL to NREL**
  - o Bi-directional communication between ESIF RTDS and INL RTDS (12/2014)
  - o Bi-directional communication between ESIF RTDS and NWTC CGI RTDS allowing real-time exchange of data (2/2015)
- **First testing completed with Giner Inc.**
  - o Performed FAT of three 150 kW PEM stacks, which were then shipped to customers in Europe
  - o Working with Giner to prepare for testing of 1/3 MW and then 1MW stacks requiring nearly 4000A DC.

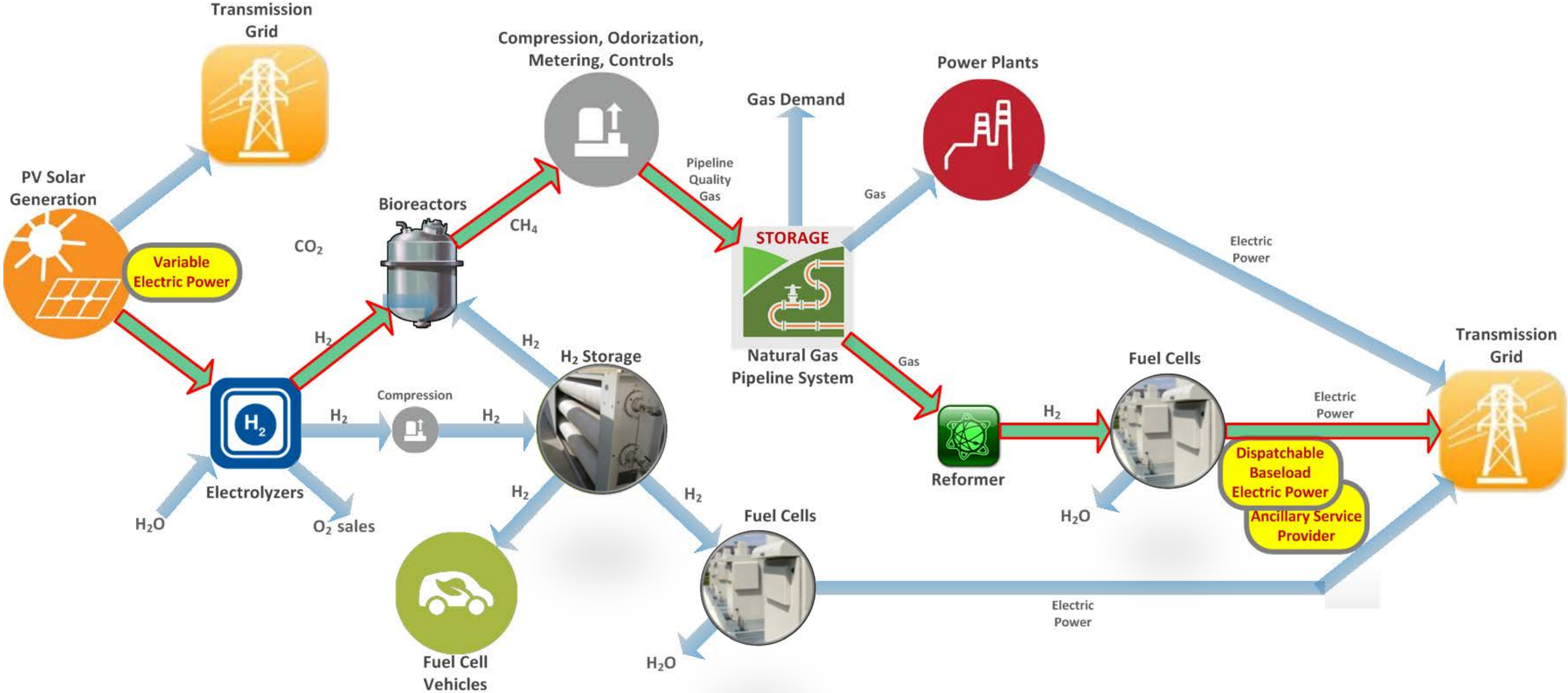
- **Currently operating 120kW stack from Proton Onsite**

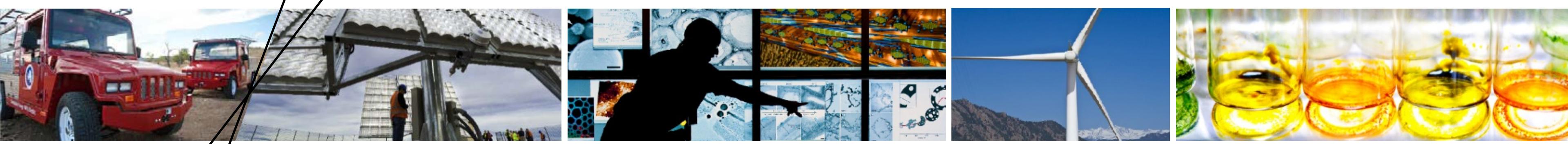
Proposed CARB-DOE Project

- **Joint CARB-DOE-NREL analysis activity**
- **Business case analysis for Power-to-gas systems in specific locations within California**
  - Near-term assessment
  - Look at several specific locations in California
  - Business case includes multi-sector integration and credit markets (i.e., electric, gas, transport, industrial supply)

NREL – SoCalGas Project

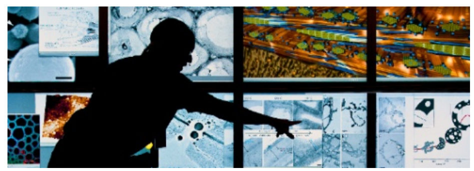
- **Goal:** Enable higher penetrations of solar power generation using the natural gas pipeline system for energy storage





Questions?

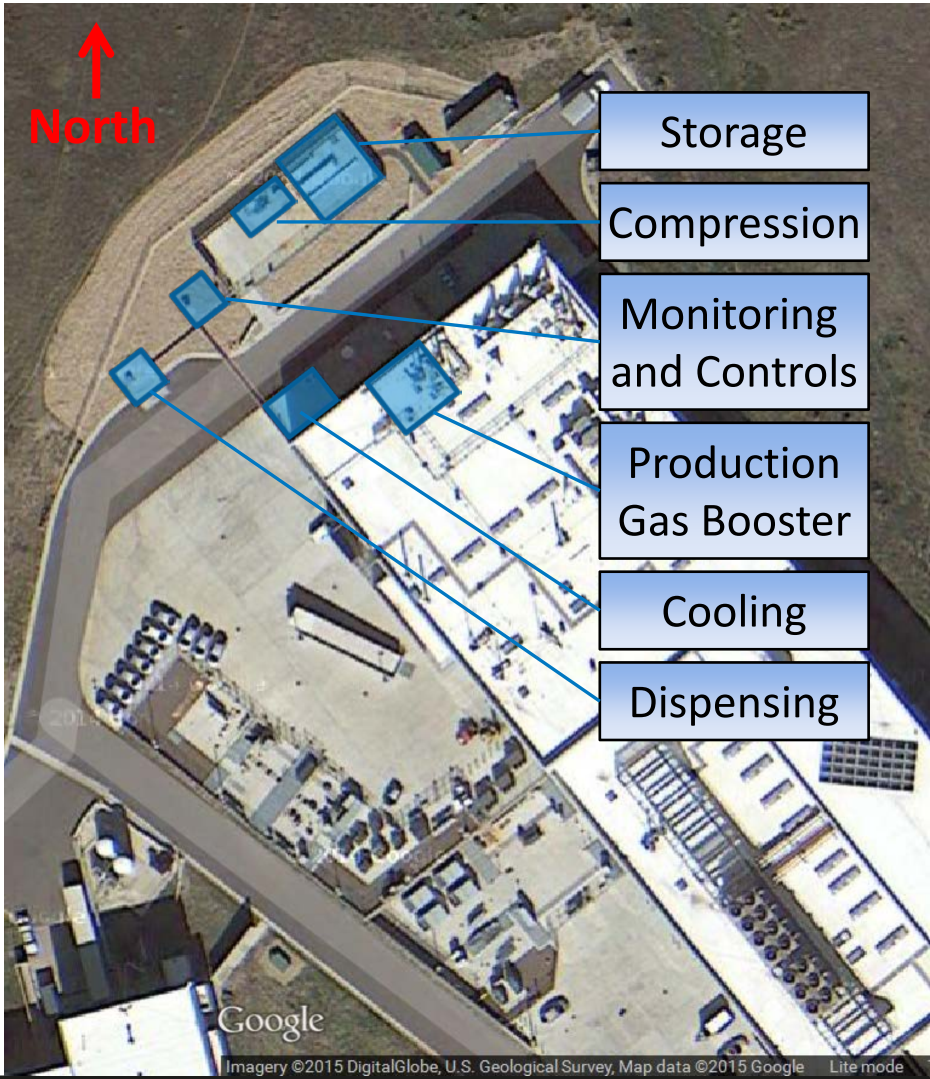
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Hydrogen Station at NREL's ESIF Facility

Hydrogen Infrastructure Testing and Research Facility (HITRF)

- **Specifications**
  - Hydrogen production via on site water electrolysis
  - Hydrogen purity testing performed every 6 months (meets SAE limits 3/1/15)
  - SAE J2601 T40 rated dispensing
  - 700 bar communication filling
  - 350 non-communication filling
  - WEH nozzle part #: TK17 & TK16
  - Cascade filling system
    - 30kg storage capacity at 860bar (12,500 psi)
    - 80kg storage capacity at 400bar (6,000 psi)
  - 20kg storage capacity at 200 bar (3,000 psi)
  - Data collection and real-time feedback on most components
  - Low ohm cement pad surrounded by blacktop driveway
- **Safety**
  - Emergency-stop located at the dispenser
  - UV/IR detector monitoring fueling area
  - Dispenser automatic shutoff when filling complete



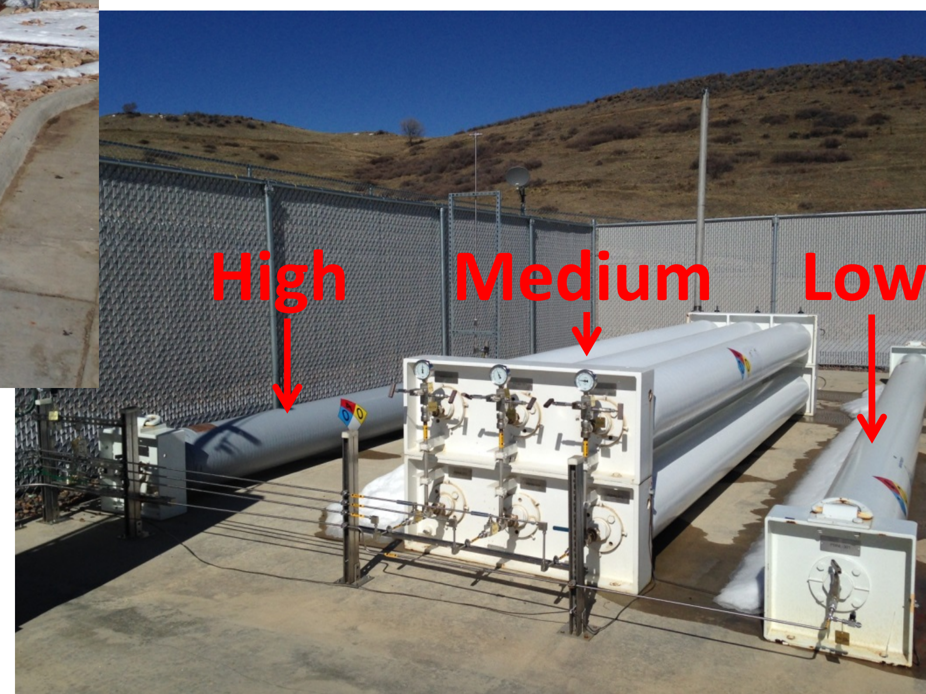
Hydrogen Station at NREL's ESIF Facility

- **Nearly Finished Commissioning Process**

High Pressure – 30kg

Medium Pressure – 80kg

Low Pressure – 20kg



700 bar communication filling

350 non-communication filling

INTEGRATE project

Integrated **N**etwork **T**estbed for **E**nergy **G**rid **R**esearch **a**nd **T**echnology **E**xperimentation

1. **Demonstrate value of integrated approach to systems - Conduct energy systems integration research to evaluate the benefits and values of EE, RE, and DER technologies at high penetration into energy infrastructures and at a variety of physical scales (single location, campus, distribution systems, regional areas)**
2. **Demonstrate value of ESIF to industry – flexible, reconfigurable experimental configurations that allows testing of a variety of technology and system configurations, operation parameters, and markets**

INTEGRATE – RTDS Communication

- **Goal**
  - Establish a first of its kind Real-time digital Simulator (RTDS) to RTDS communications network between NREL's ESIF and INL
- **Accomplishment:**
  - Successful data exchange from INL to NREL
    - Bi-directional communication test between ESIF RTDS and INL RTDS (December 2014)
    - Bi-directional communication between ESIF RTDS and NWTC CGI RTDS allowing real-time exchange of data (February 2015)
  - Model-to-model communication tested
    - 13 node feeder model at NREL and Kundur 2-area system model at INL) one-way from INL to NREL
  - INL data feeds into NREL model but NREL data does not yet feed into INL model