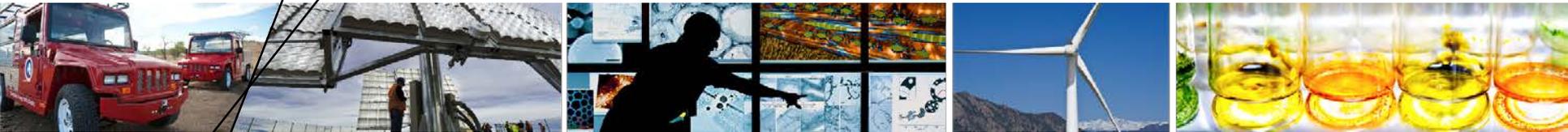


Hydrogen Energy Storage (HES) Activities at NREL



HTAC

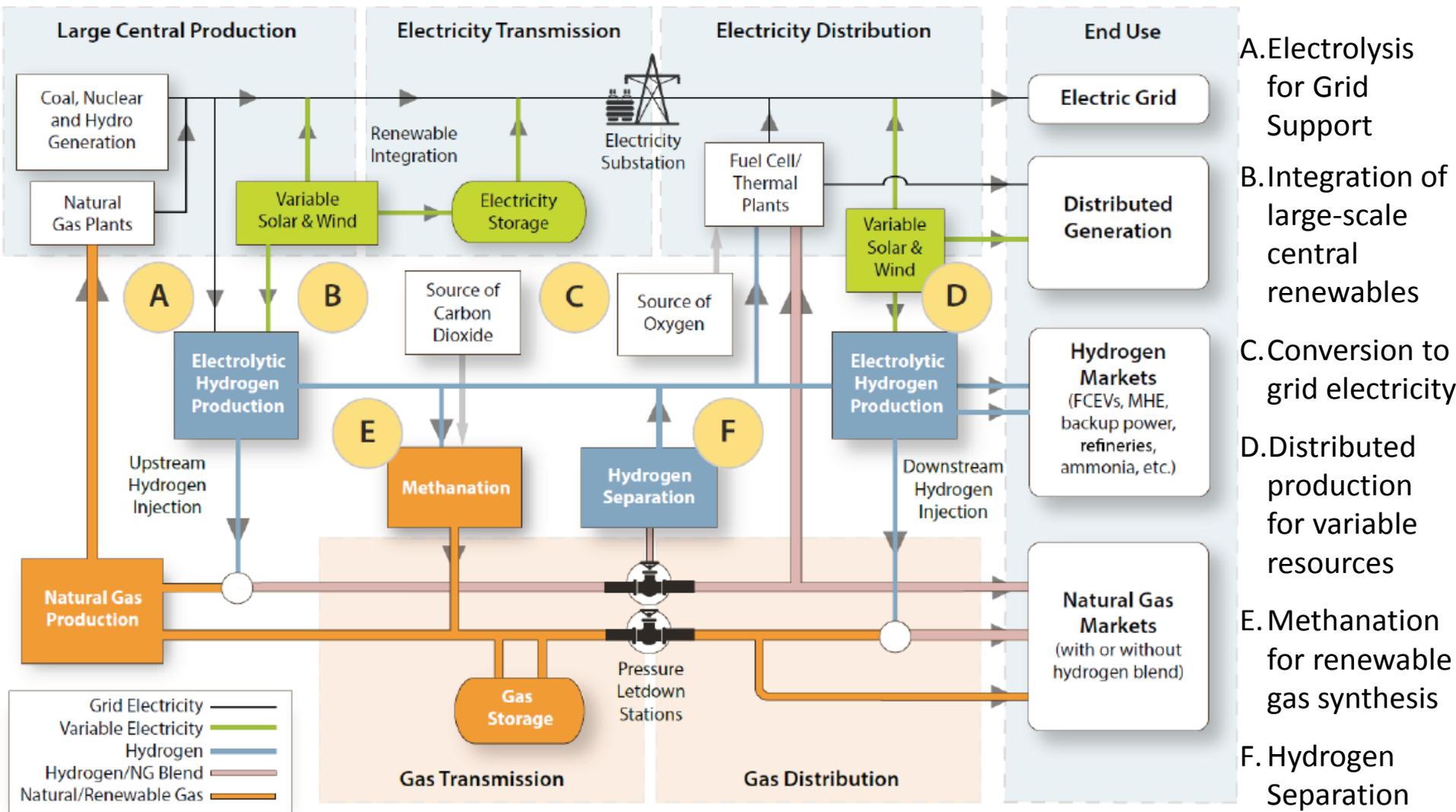
Josh Eichman, PhD

4/21/2015

Outline

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

Hydrogen energy storage pathways



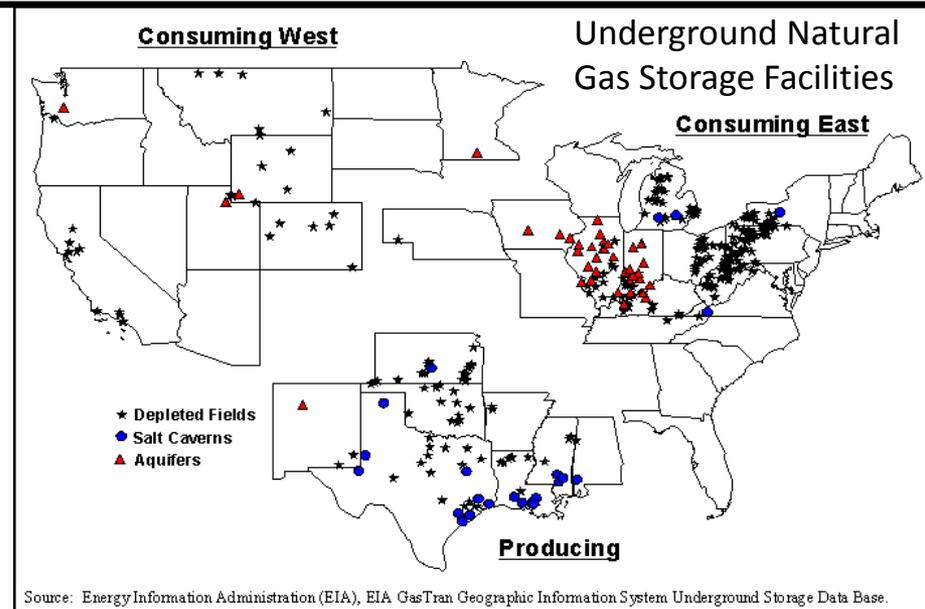
Source: <http://www.nrel.gov/docs/fy15osti/62518.pdf>

Opportunities for Power-to-gas

- **Natural Gas System**

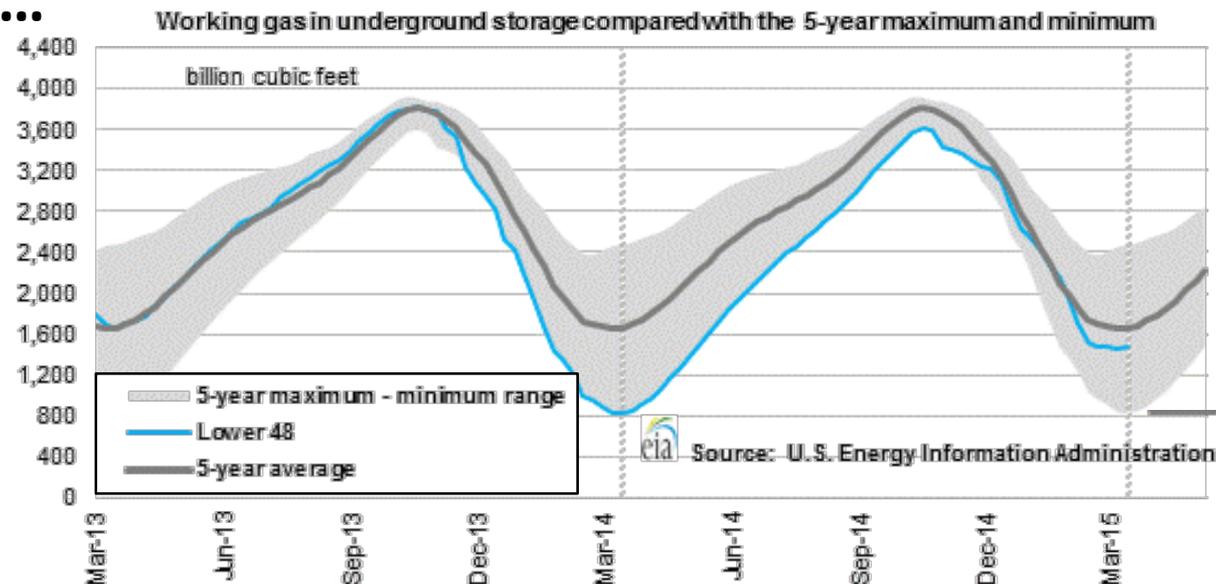
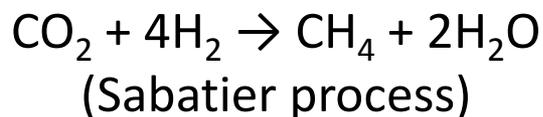
- 305,000 miles of transmission pipelines
- 400 underground natural gas storage facilities
- 3.9 Bcf underground storage working gas capacity

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



- **Storage equates to...**

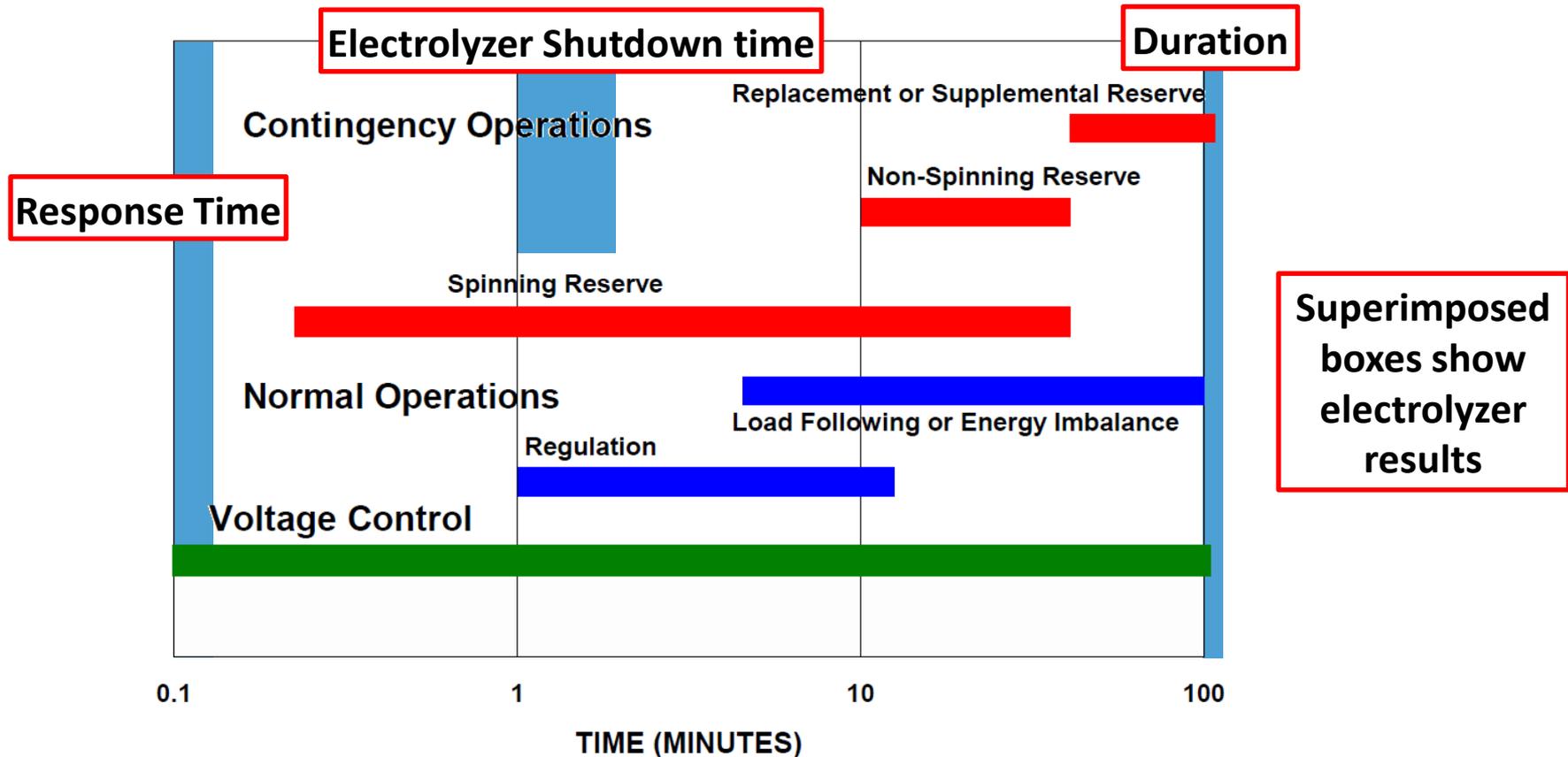
- 38 billion kg of H₂ used to produce CH₄ from CO₂ methanation for one fill



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

```
graph LR; A[Historical or Modelled] --> B[Optimization model]; B --> C[Profit based on operation (arbitrage, AS, H2 sale, etc.)]
```

Optimization model

Profit based on operation (arbitrage, AS, H₂ 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: ¹EPRI 2010, Electricity Energy Storage Technology Options, 1020676

²EIA 2012, Annual Energy Outlook

³DOE 2011, DOE Hydrogen and Fuel Cells Program Plan

⁴H2A Model version 3.0

⁵NREL 2009, NREL/TP-560-46719 (only purchase once if using FC&EY system)

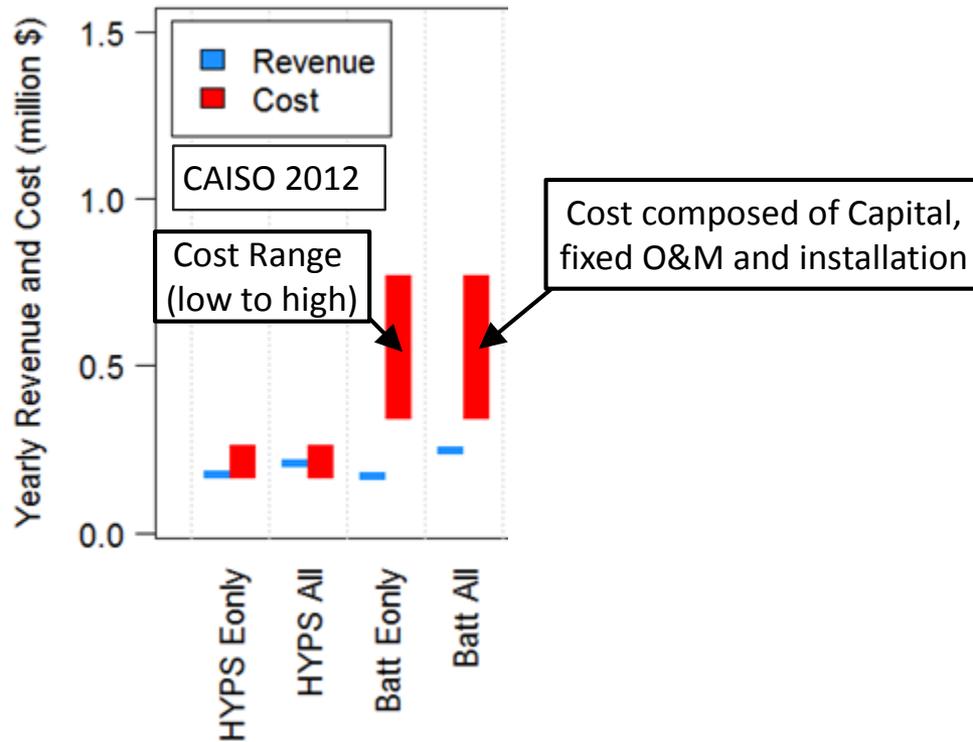
⁶NREL 2008, NREL/TP-550-44103

⁷Levine, 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



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

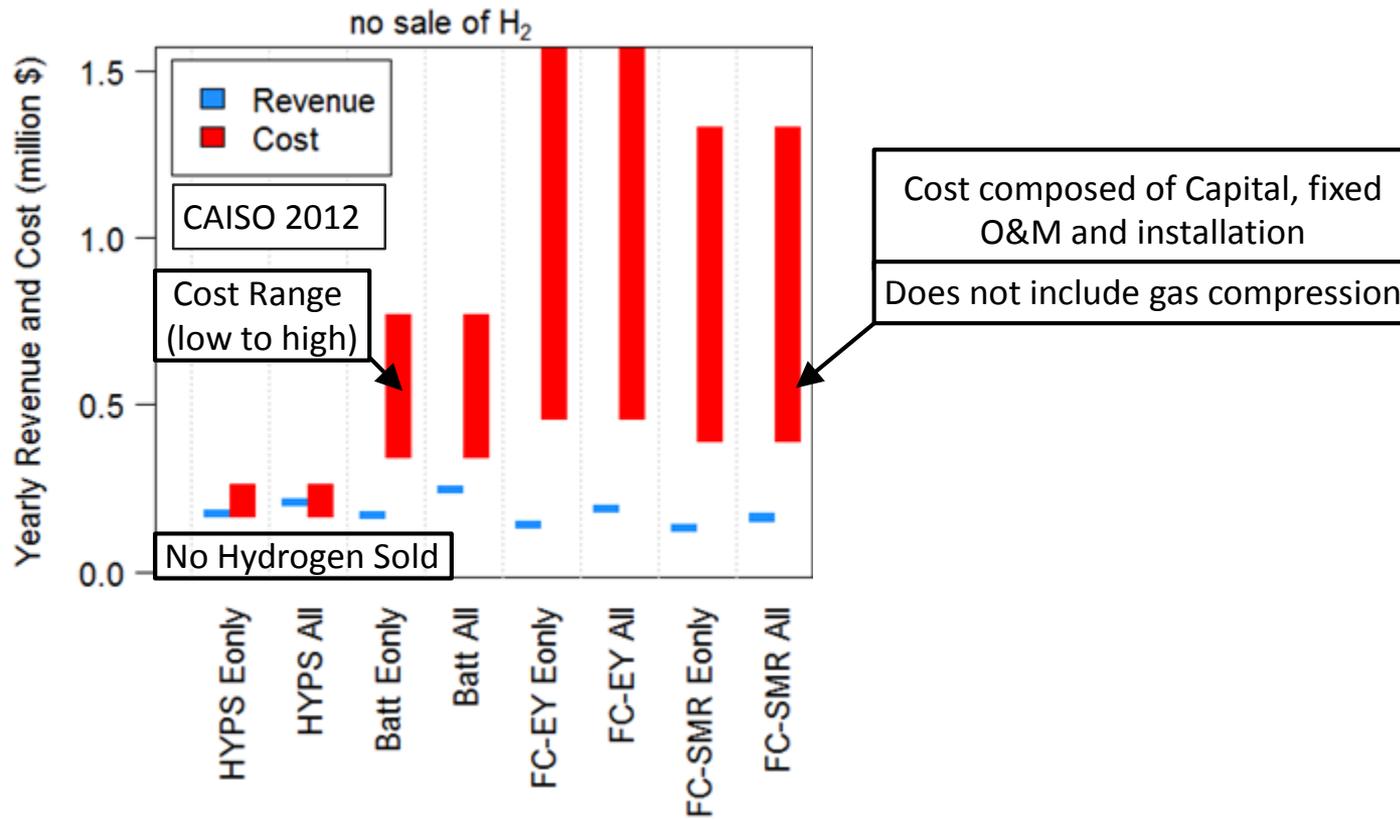
Name	Services
All	All Ancillary Services
Eonly	Energy Arbitrage only
Baseload	“Flat” operation

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

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



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

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

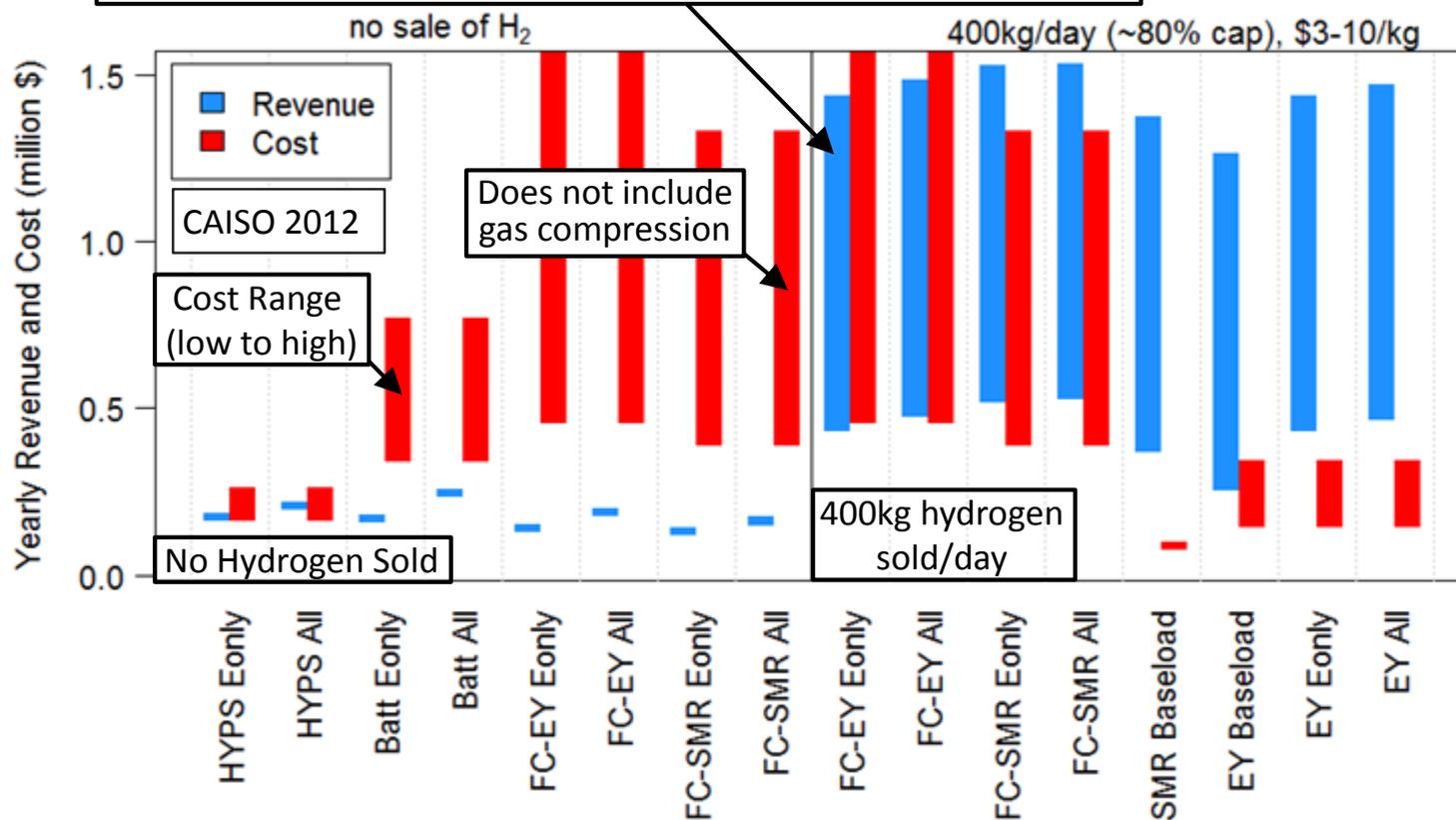
Price-Taker Results with historical prices

Selling hydrogen increases competitiveness

Providing ancillary services > Energy only > Baseload

Electrolyzers providing demand response are promising

Range of potential prices at which hydrogen can be sold (\$3-10/kg)



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

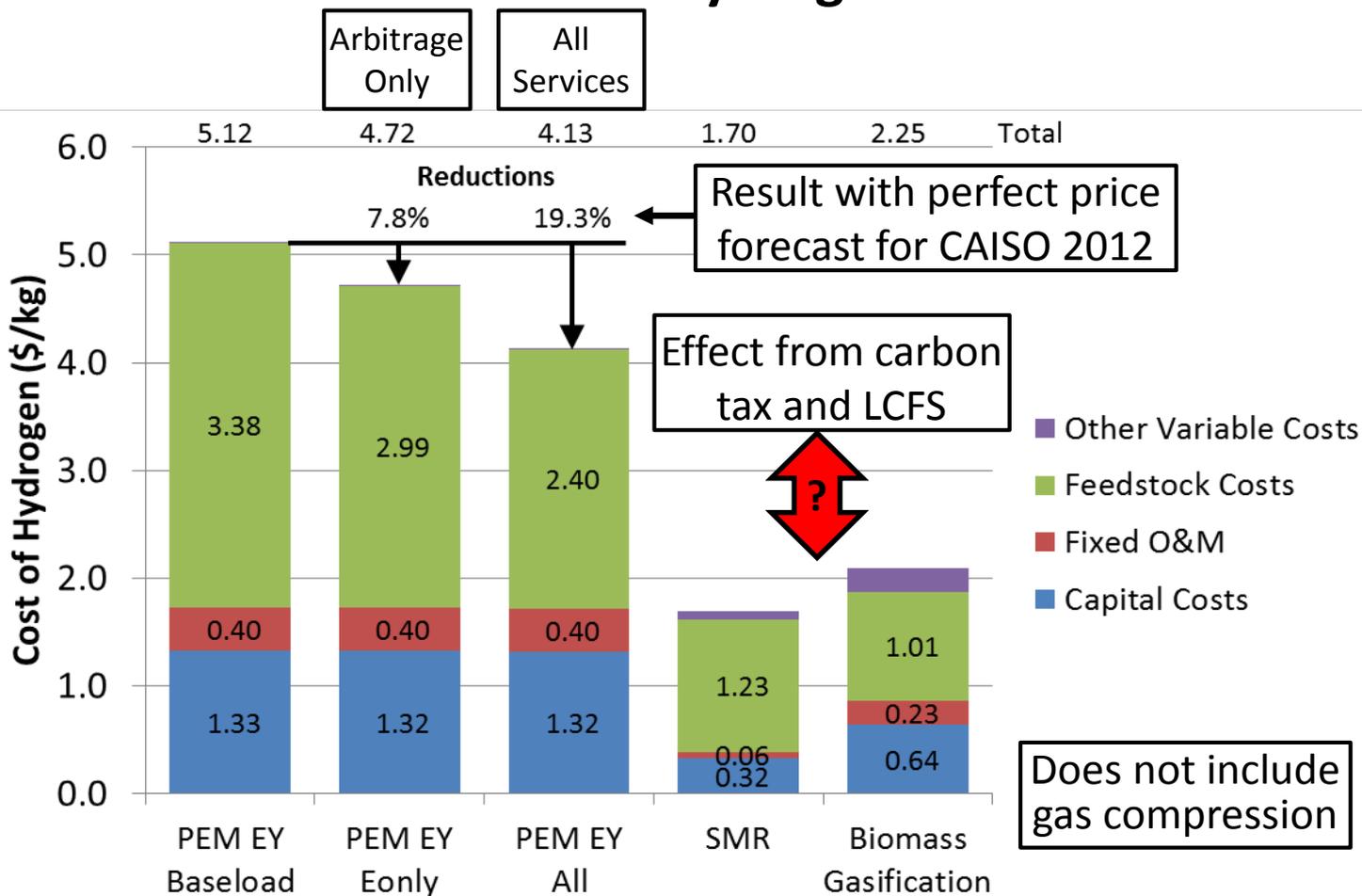
Name	Services
All	All Ancillary Services
Eonly	Energy Arbitrage only
Baseload	"Flat" operation

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

Value for H₂ Grid Integration

Integration with the grid can lower feedstock costs and increase revenue

• H2A Current Central Hydrogen Production



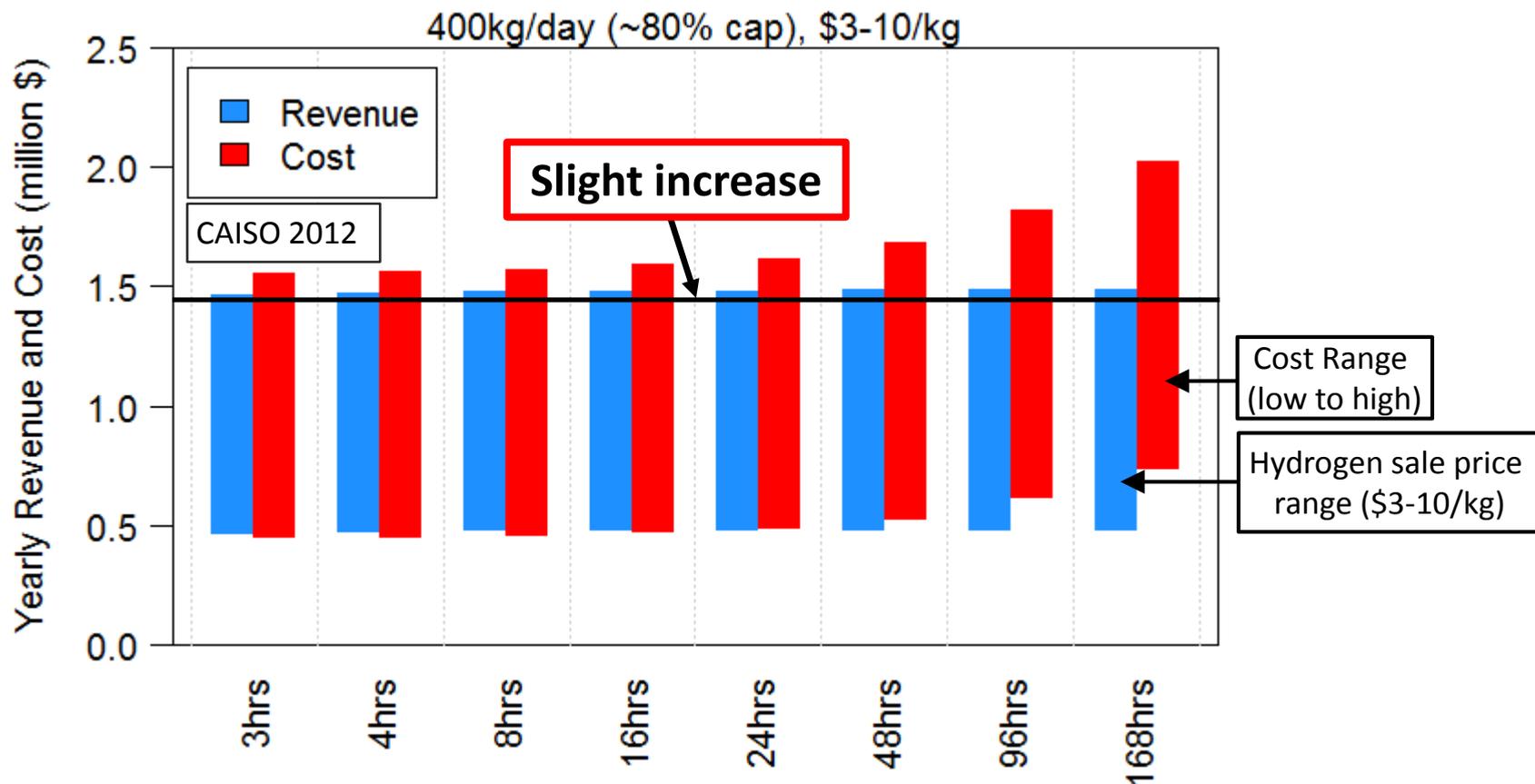
Name	Technology
HYPS	Pumped Hydro
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Name	Services
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Eonly	Energy Arbitrage only
Baseload	"Flat" operation

Energy Capacity Sensitivity Analysis

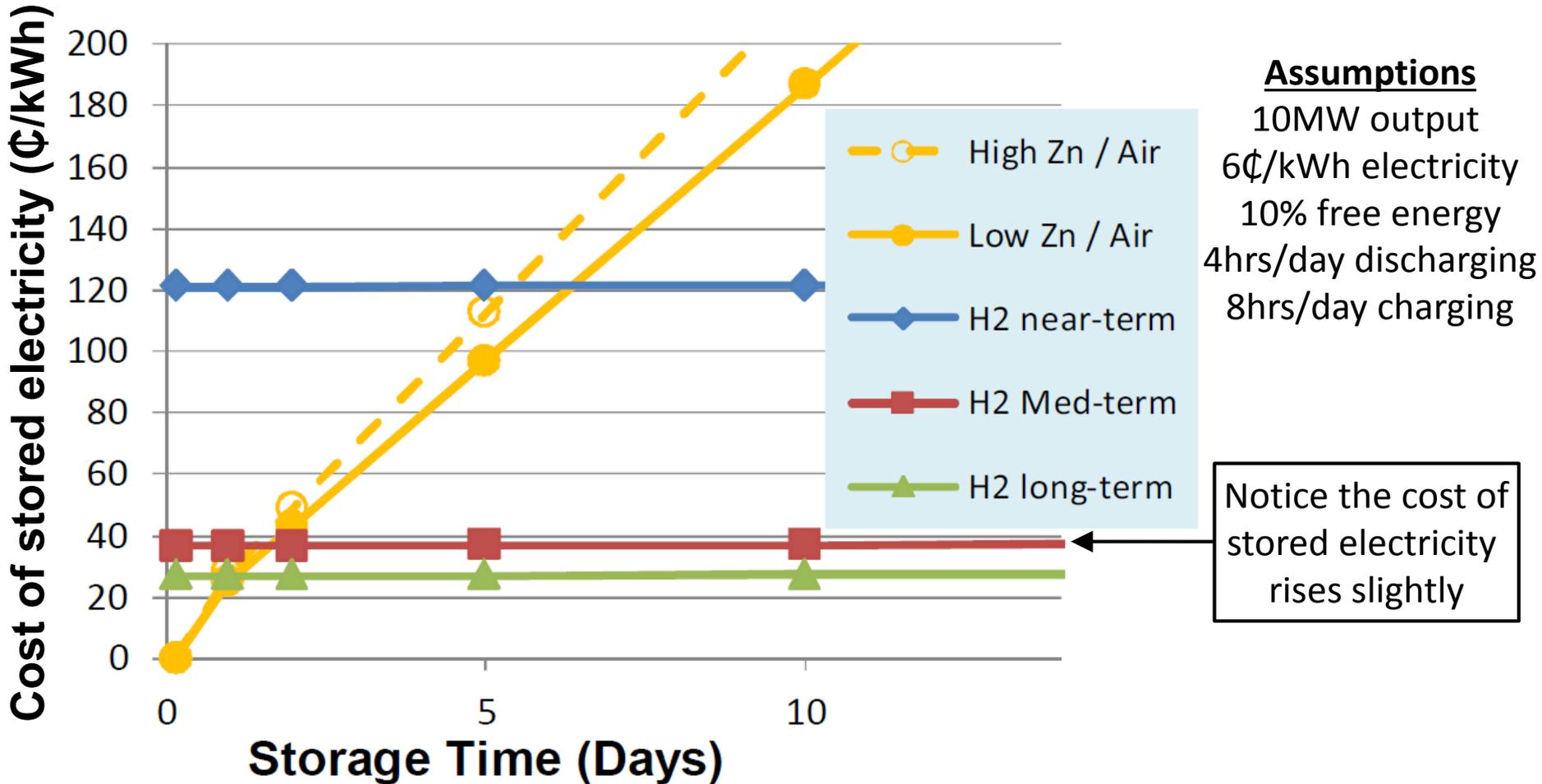
More storage is not necessarily more competitive in current energy and ancillary service markets

- 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



Electrolytic Hydrogen Production Workshop (NREL 2/2014)

Objective: Discuss and share information on RD&D needs for enabling low-cost, effective hydrogen production from all types of water electrolysis systems, both centralized and forecourt

- **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 H₂ 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**

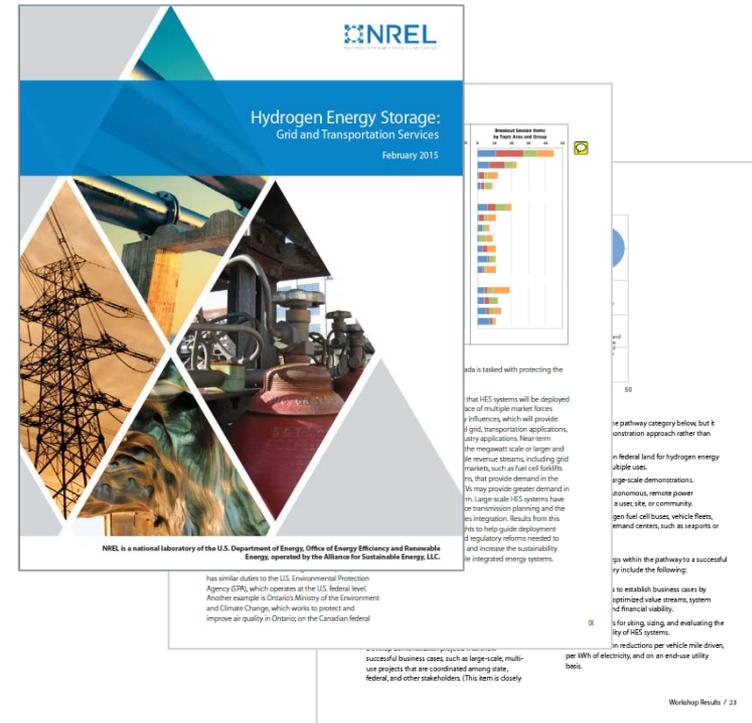
- Launched on February 19, 2009
- Enhance bilateral collaboration for clean energy science and technologies to reduce GHGs and combat climate change.
- Support efforts to build a low-carbon North American economy

- **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)
- Quantify electricity market size

INTEGRATE – Integrated Network Testbed for Energy Grid Research and Technology Experimentation

Objective: Demonstrate value of integrated approach to evaluating EE, RE & DER

- **Completed the design, installation and commissioning of a 250 kW stack test bed**
 - AC/DC power supplies are capable of 500 kW
- **Successful data exchange from INL to NREL**
 - Bi-directional communication between ESIF RTDS and INL RTDS (12/2014)
 - Bi-directional communication between ESIF RTDS and NWTC CGI RTDS allowing real-time exchange of data (2/2015)
- **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**

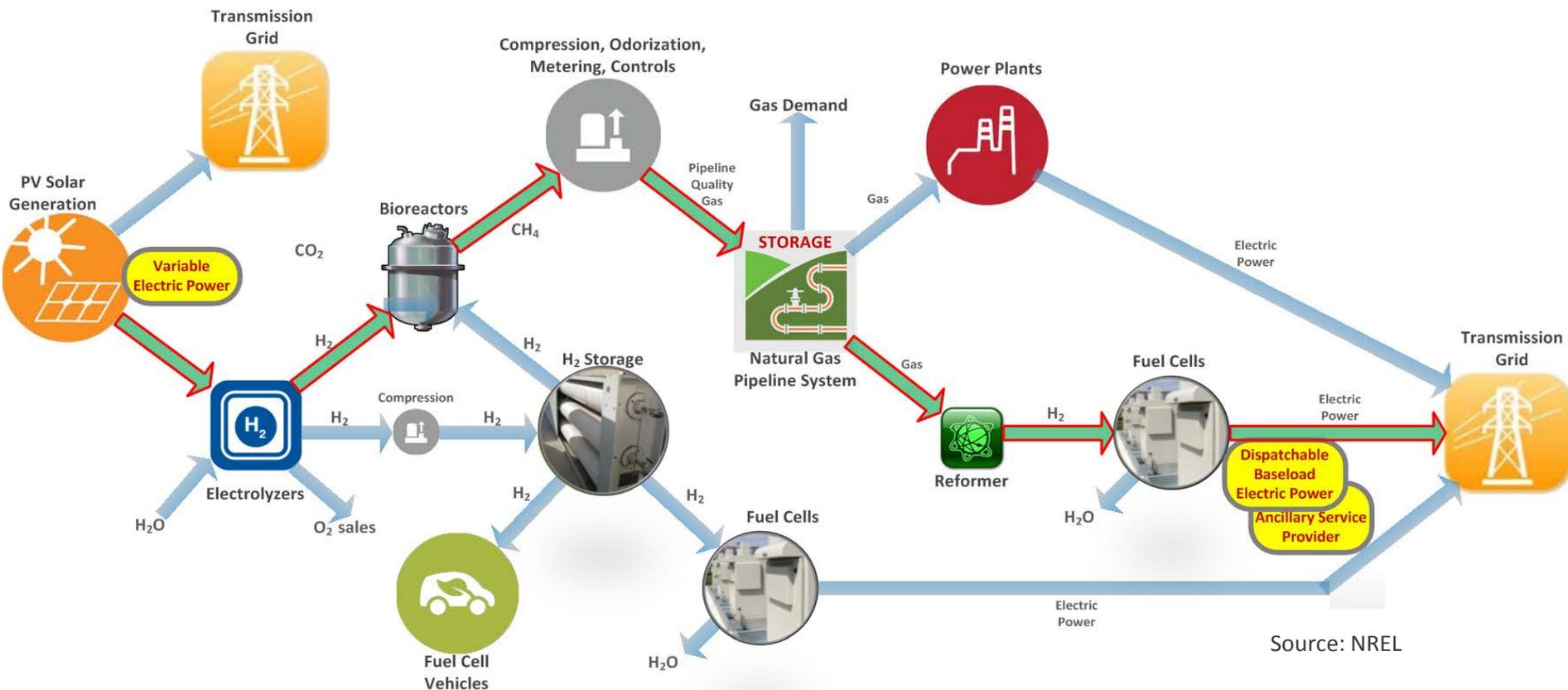


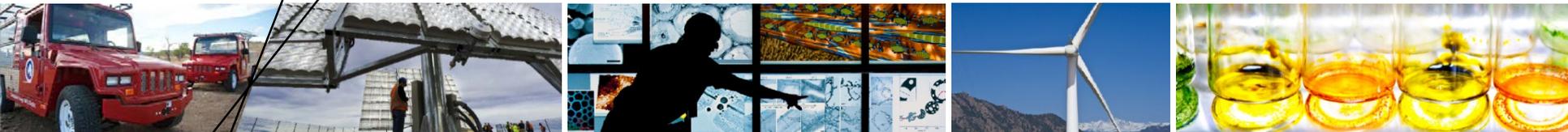
Proposed CARB-DOE Project

- **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?

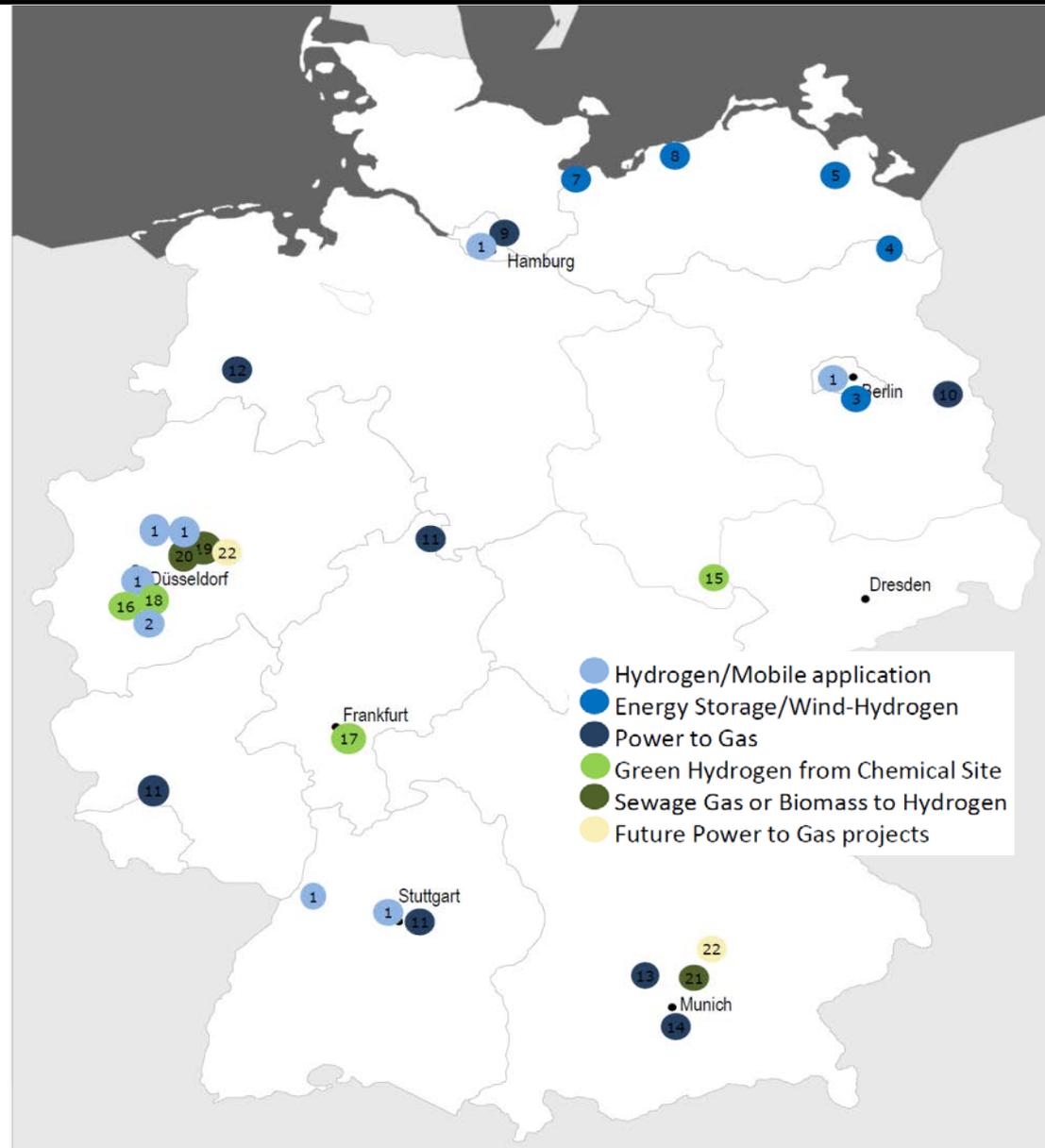
Hydrogen storage and Power-to-gas (PtG) projects

- **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



Hydrogen Station at NREL's ESIF Facility

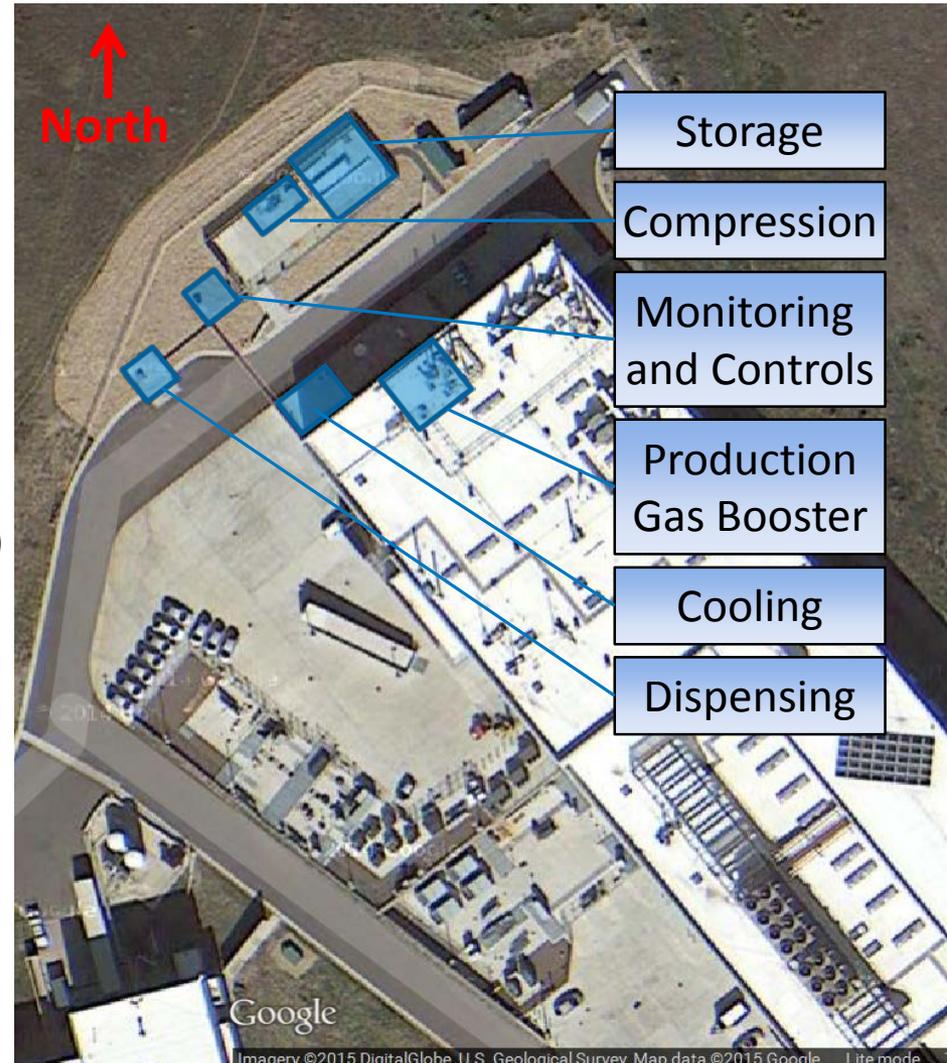
Hydrogen Infrastructure Testing and Research Facility (HITRF)

- **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)
- 20 kg 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



700 bar communication filling
350 non-communication filling

High Pressure – 30 kg
Medium Pressure – 80 kg
Low Pressure – 20 kg





Integrated Network Testbed for Energy Grid Research and Technology Experimentation

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

