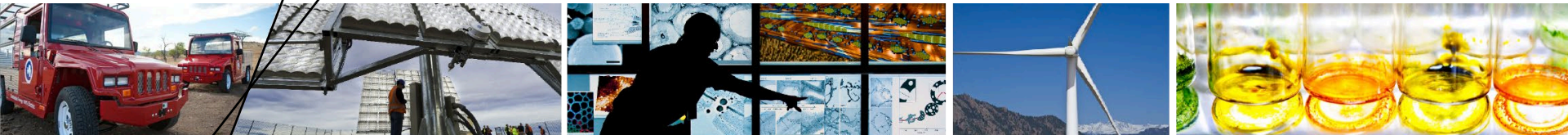


Hydrogen Energy Storage (HES) and Power-to-Gas Economic Analysis



CHBC Summer Summit

Josh Eichman, PhD

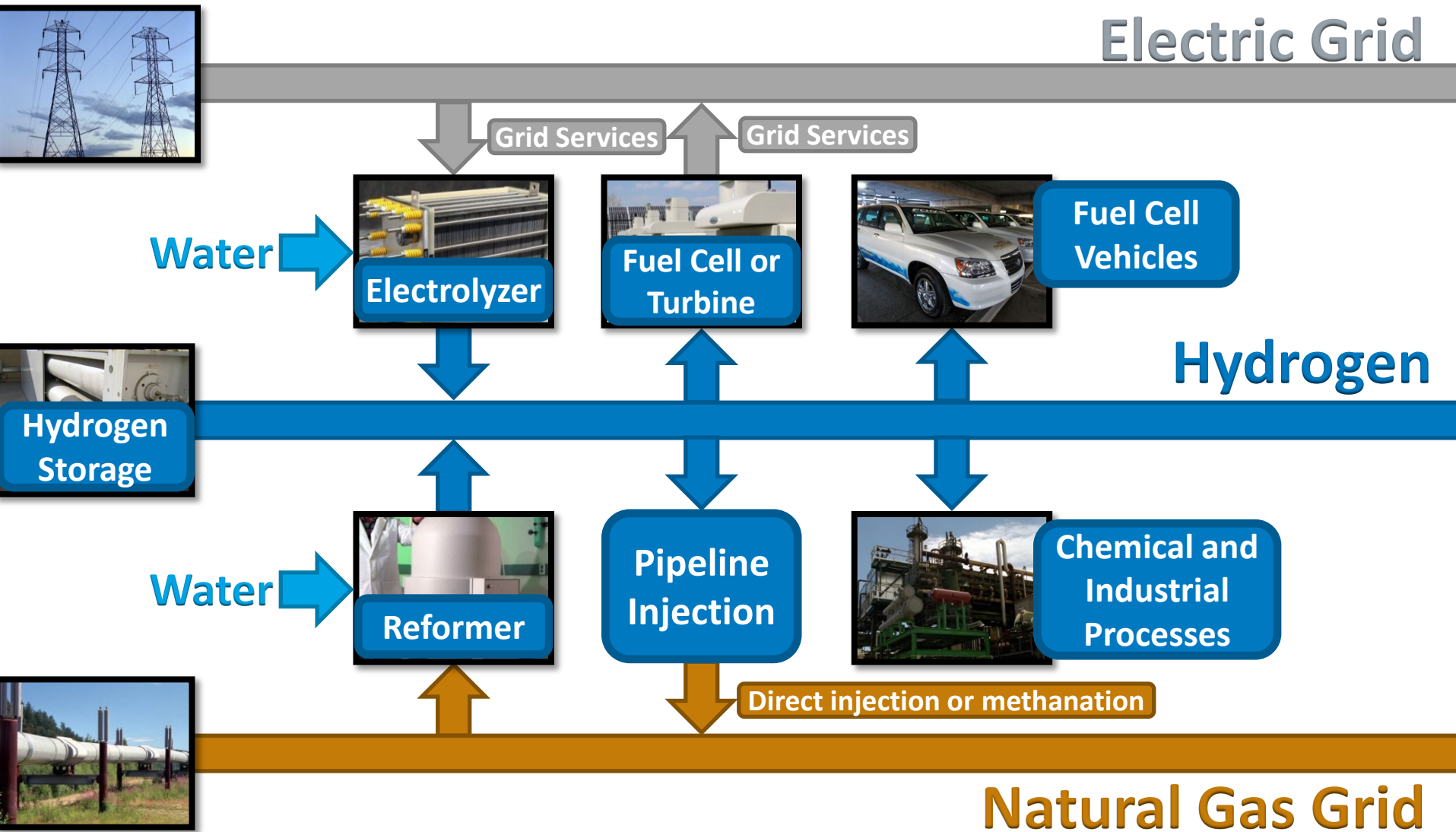
Downey, California

7/30/2015

Outline

- **Opportunity for HES / P2G**
- **Markets considered**
- **Market valuation results**
- **Future market expectations**
- **Additional projects**

Complementary Hydrogen Systems



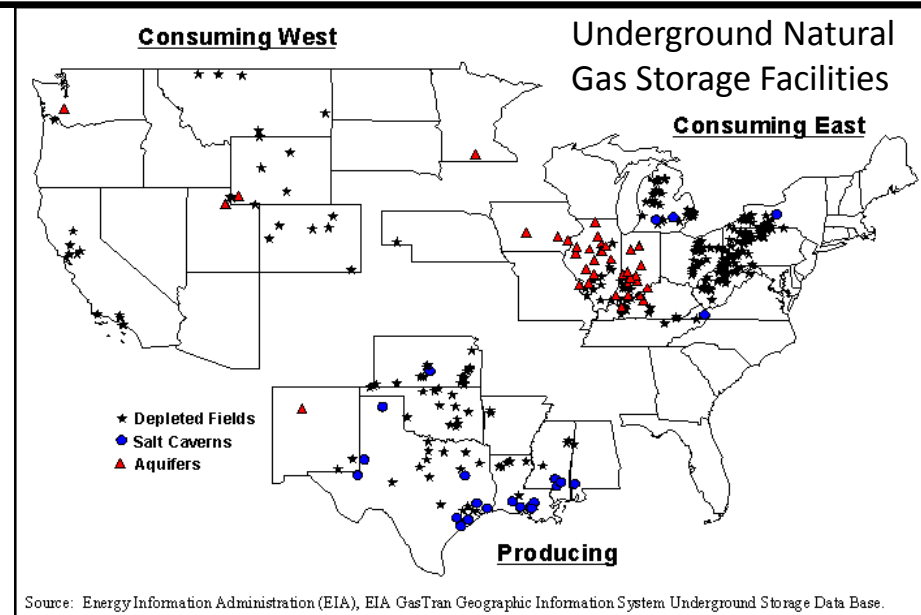
Source: (from top left by row), Warren Gretz, NREL 10926; Matt Stiveson, NREL 12508; Keith Wipke, NREL 17319; Dennis Schroeder, NREL 22794; NextEnergy Center, NREL 16129; Warren Gretz, NREL 09830; David Parsons, NREL 05050; and Bruce Green, NREL 09408

Opportunities for Power-to-gas

- **Natural Gas System**

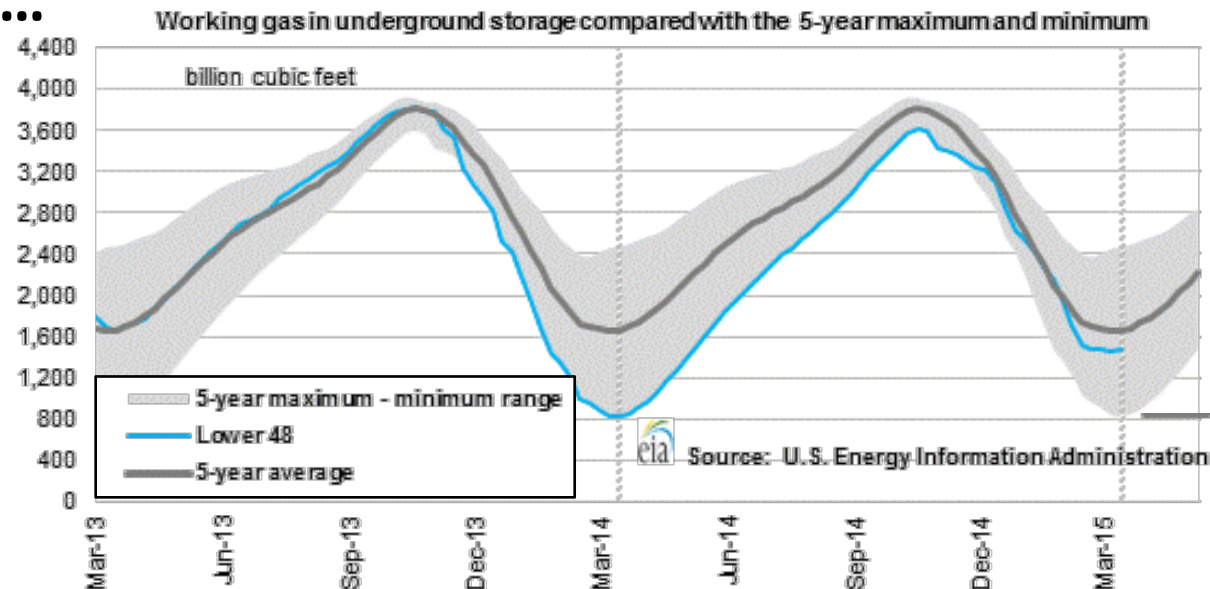
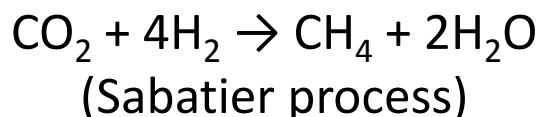
- 305,000 miles of transmission pipelines
- 400 underground natural gas storage facilities
- 3.9 Bcf underground storage working gas capacity

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



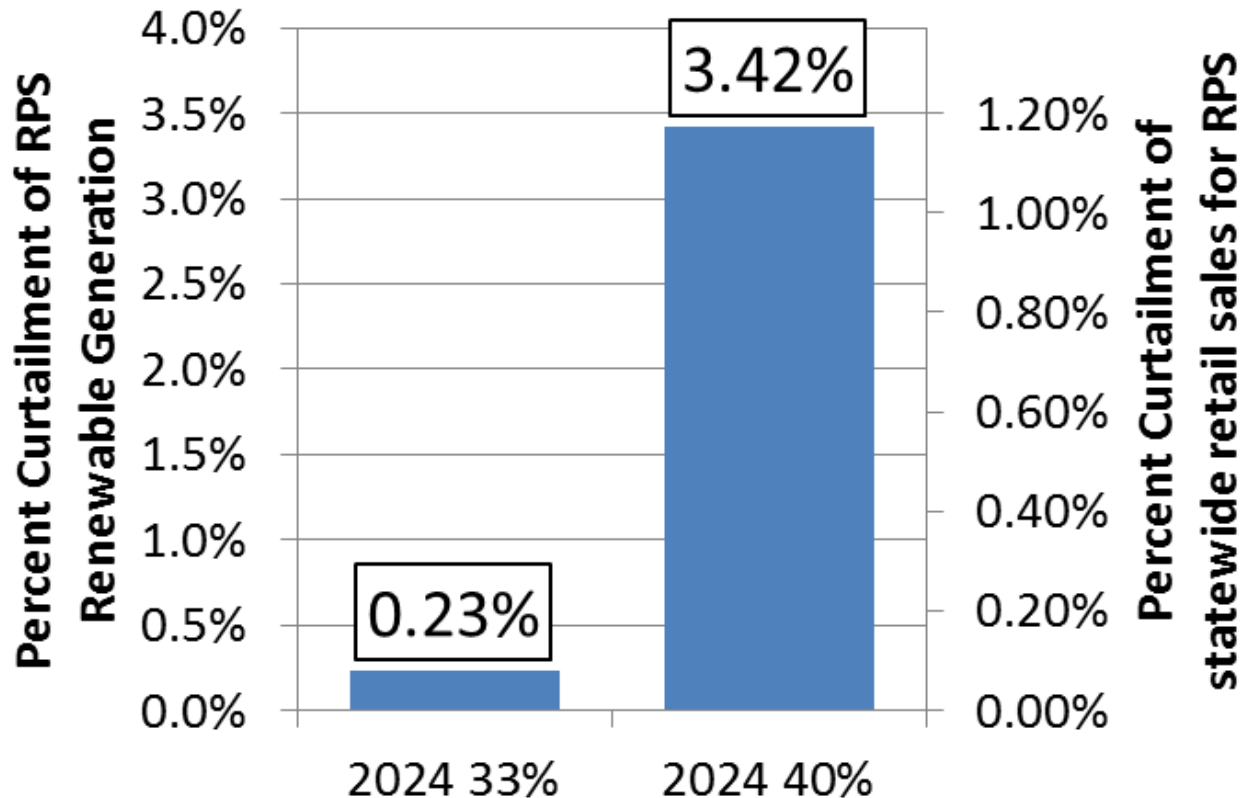
- **Storage equates to...**

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



Expected Curtailment from CAISO model

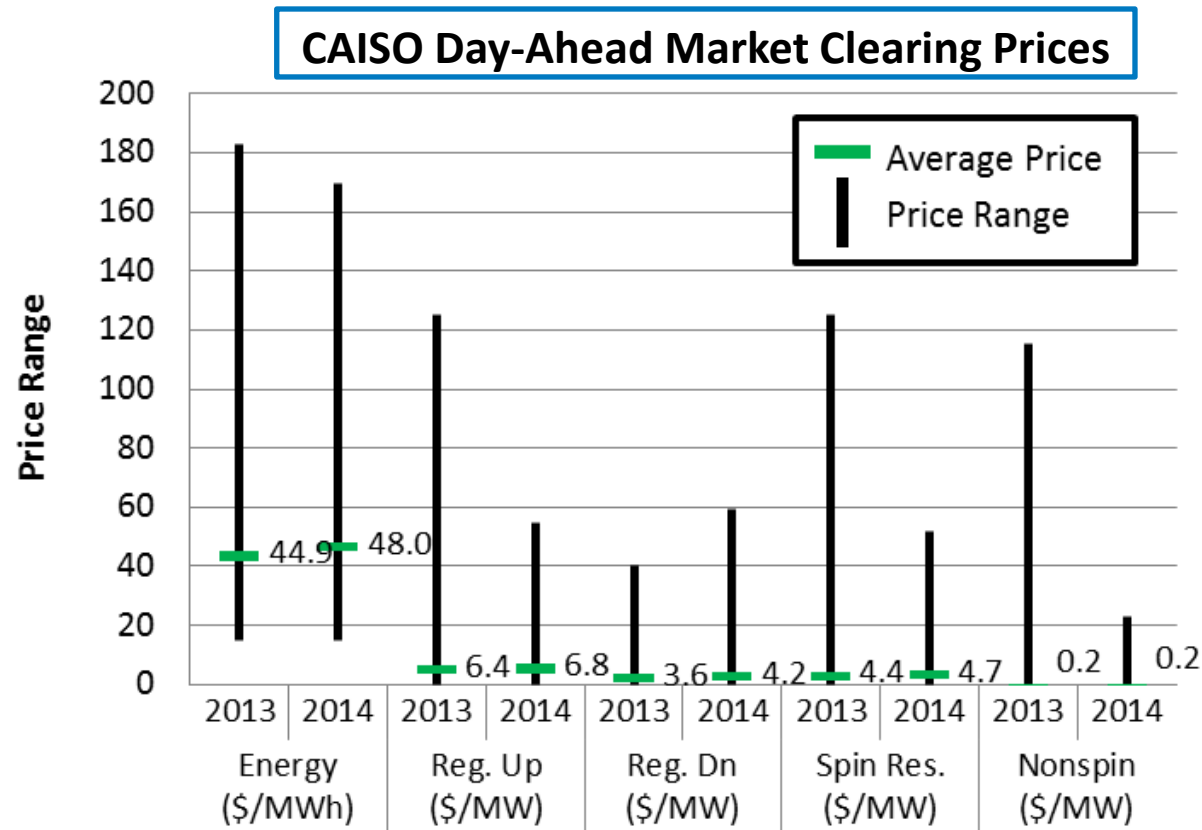
- Results from CAISO 2014 LTPP model (Long Term Procurement Plan)



Source: http://www.caiso.com/Documents/Aug13_2014_InitialTestimony_ShuchengLiu_Phase1A_LTPP_R13-12-010.pdf

Market value varies for services provided

- **Energy**
 - Electric Price
- **Ancillary Services**
 - Voltage Support
 - Load-Following Up/Down
 - Regulation Up/Down
 - Spinning Reserve
 - Non-Spin Reserve
 - Black Start
- **Capacity**
 - \$150/kW-year



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

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 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	Lithium Ion 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	3850 ¹ - 4100 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 (4500cycles)	20	20 ⁴	20 ⁴
Interest rate on debt	10%	10%	10%	10%	10%
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)

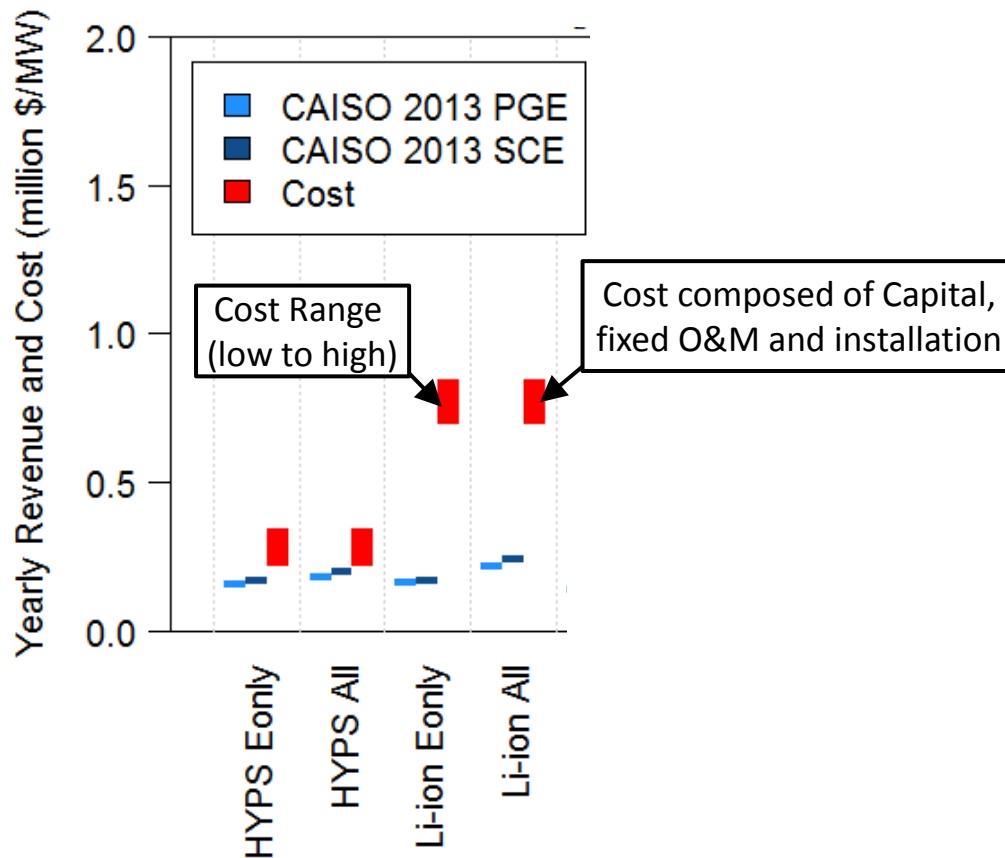
⁶NREL 2008, NREL/TP-550-44103

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



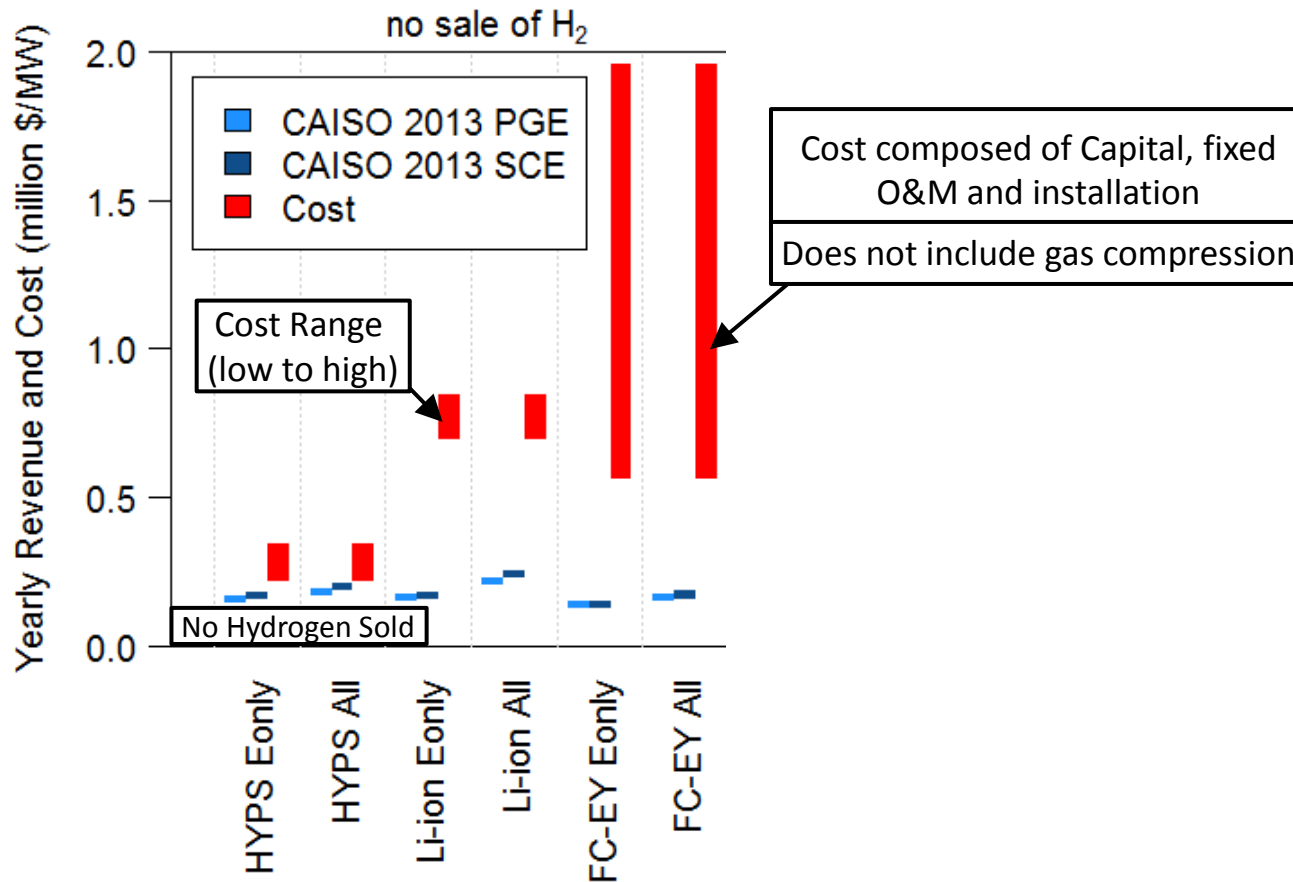
Name	Technology
HYPs	Pumped Hydro
Li-ion	Lithium-Ion
FC	Fuel Cell
EY	Electrolyzer
SMR	Steam Methane Reformer

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, system costs must be reduced to improve competitiveness

- Comparison of yearly revenue and cost



Name	Technology
HYPS	Pumped Hydro
Li-ion	Lithium-Ion
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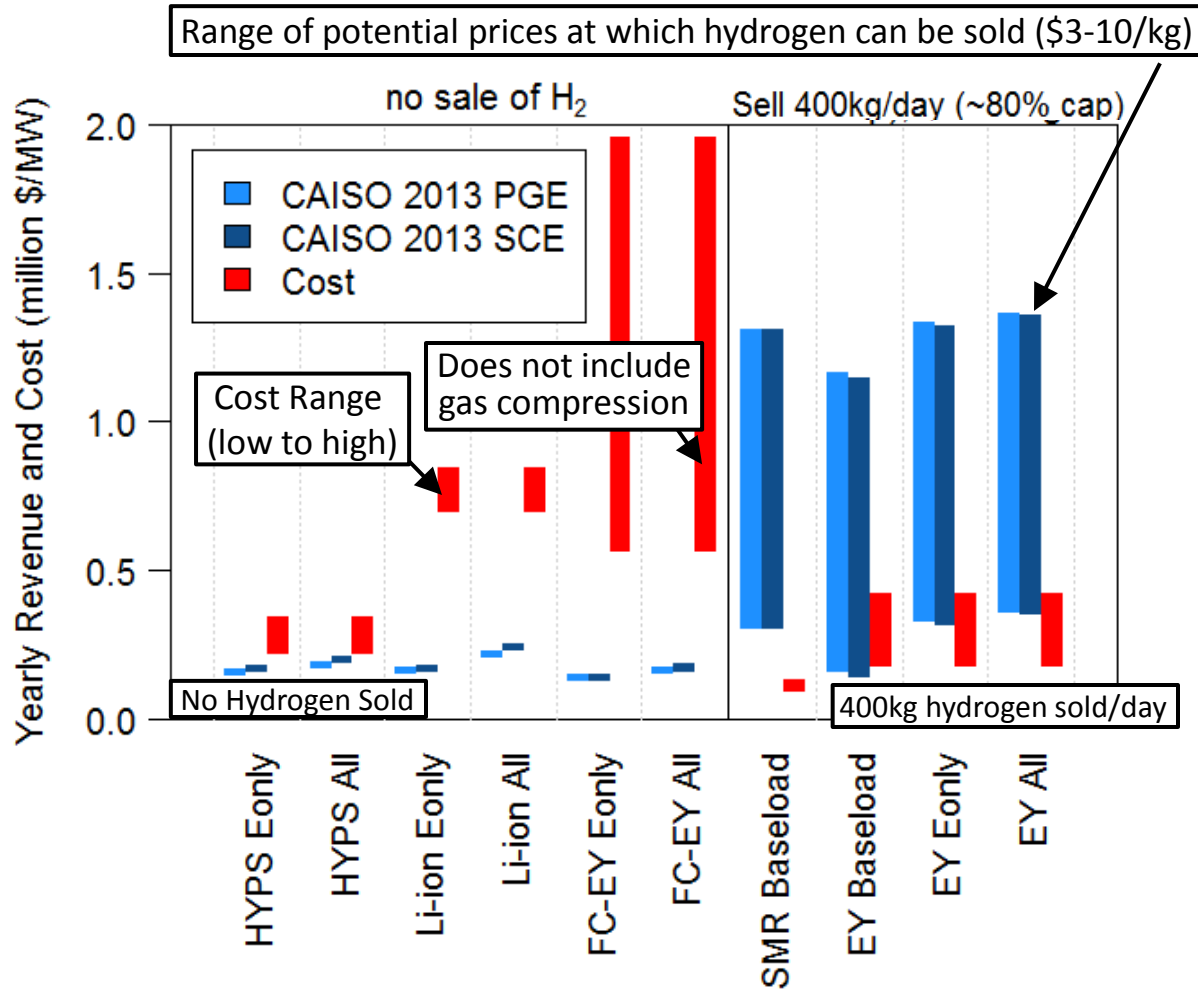
Name	Services
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Price-Taker Results with historical prices

Selling hydrogen increases competitiveness

Providing ancillary services > Energy only > Baseload

Electrolyzers providing demand response are promising opportunity



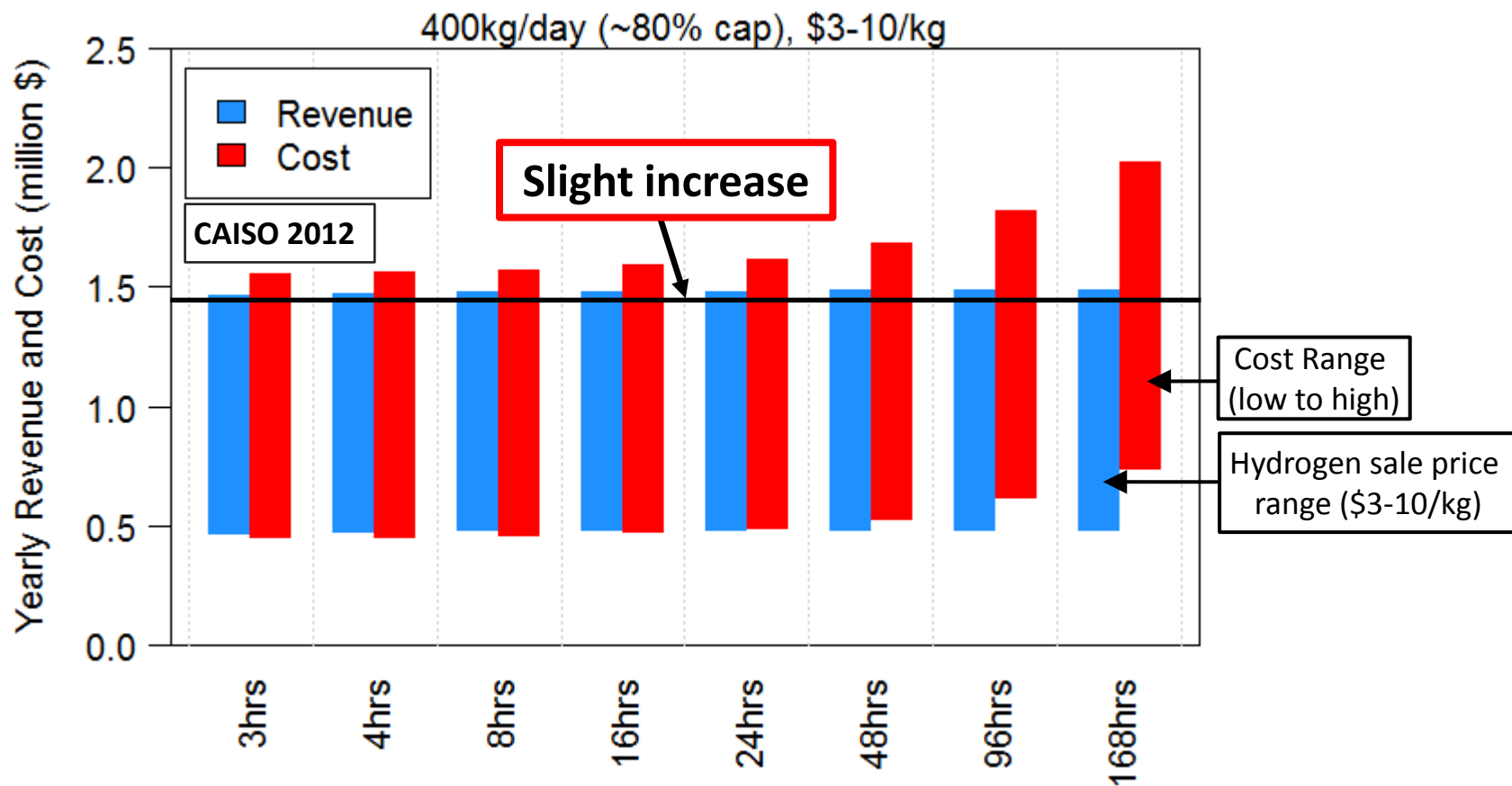
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Baseload	"Flat" operation

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



Future market expectations

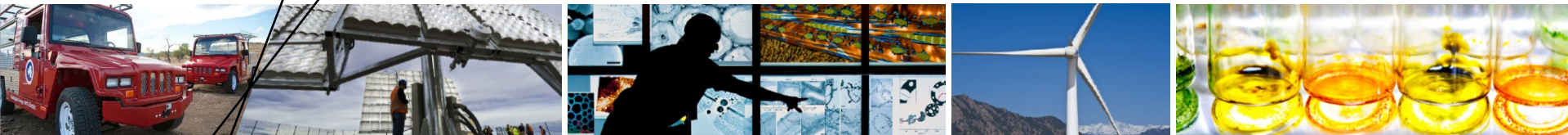
Impacts from variable generation (VG)...

- **Energy Markets**
 - Reduce Locational Marginal Prices (LMP)
 - More occurrences of zero or negative LMP periods
 - More volatile LMPs caused by increased variability
 - Greater need for flexible resources in the energy market
- **Ancillary Services**
 - Increase the requirements for normal balancing reserve, which can increase the prices for those services.
 - More frequent price spikes as a result of higher balancing reserve demands and increased variability and uncertainty
 - May require greater flexibility from the resources that correct for its variability and uncertainty.
- **Capacity Markets**
 - Increase in resources providing capacity rather than energy because of reduction in LMPs
 - May require planning and building more flexible resources to prepare for future needs rather than focusing on the need for megawatt capacity alone.

More information is available at http://www.nrel.gov/electricity/transmission/electricity_market.html

Other Relevant Projects

- **NREL – DOE storage analysis activities for FY15**
 - Further quantify value of HES
 - Explicit spatial modeling
 - Infrastructure opportunities
 - Expand use of data (years, locations)
- **California Specific Power-to-gas business case assessment**
 - Joint CARB-DOE-NREL analysis activity
 - Business case analysis for Power-to-gas systems
 - 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: Power-to-Gas project**



Questions?