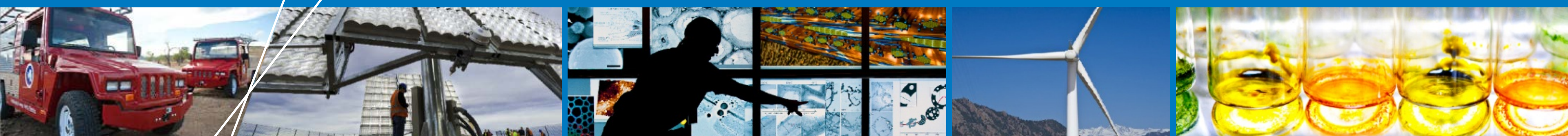
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Electricity Market Valuation for Hydrogen Technologies



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6/17/2014

AN049

Overview

Timeline

Project start date: January 2013

Project end date: January 2015

Percent complete: 70%

Barriers

4.5 A. Future Market Behavior

4.5 B. Stove-piped/Siloed Analytical Capability

4.5 D. Insufficient Suite of Models and Tools

Budget

FY13 DOE Funding: $85k

Planned FY14 DOE Funding: $115k

Total DOE Project Value: $200k

Partners

- **Interactions / Reviewers**
  - Xcel Energy
  - FuelCell Energy
  - Versa Power
  - ITM Power
  - Proton Onsite
  - NREL
- **Project Team**
  - Josh Eichman

Electricity Market Valuation

Electricity Market Valuation for grid integration of Hydrogen Technologies

Analysis Framework

- Electrolyzer Operation Data (NWTC)
- H2A design parameters
- Electric Market Data
- EIA, EPRI and NREL cost parameters

Models & Tools

- Price-Taker co-optimization Model
- Cost comparison model

Studies & Analysis

Valuation of electricity markets to enhance revenue for hydrogen technologies

- Electricity market valuation
- Technology cost comparison

Outputs & Deliverables

Detailed understanding of flexibility of hydrogen technologies and value of grid integration

- Electrolyzer flexibility paper
- Hydrogen grid integration paper

Interactions

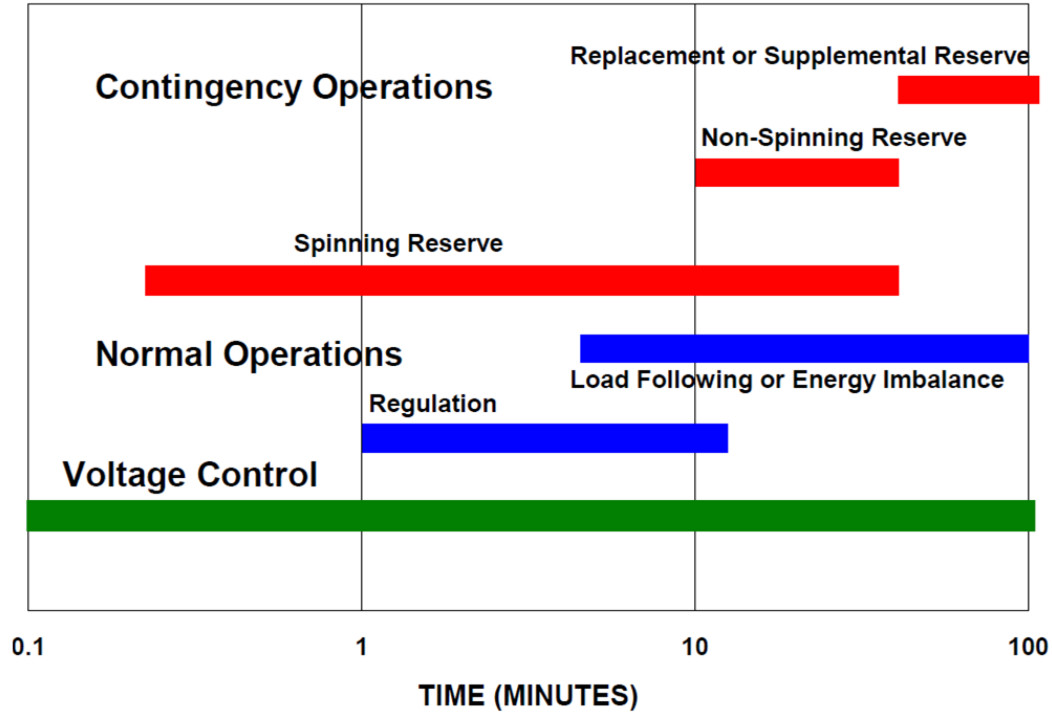
Xcel Energy
FuelCell Energy
Versa Power
ITM Power
Proton Onsite

NREL, DOE Fuel Cell Technologies Office, Internal & External Reviews

Objective #1

Evaluate the ability of electrolyzers to bid into electricity markets

- **Integration into electricity markets enables additional revenue streams [4.5A,B]**
  - Energy Market
  - Ancillary Service Markets
  - Capacity Market
- **Understanding the flexibility of hydrogen technologies is critical to assessing their ability to integrate with the grid [4.5B]**

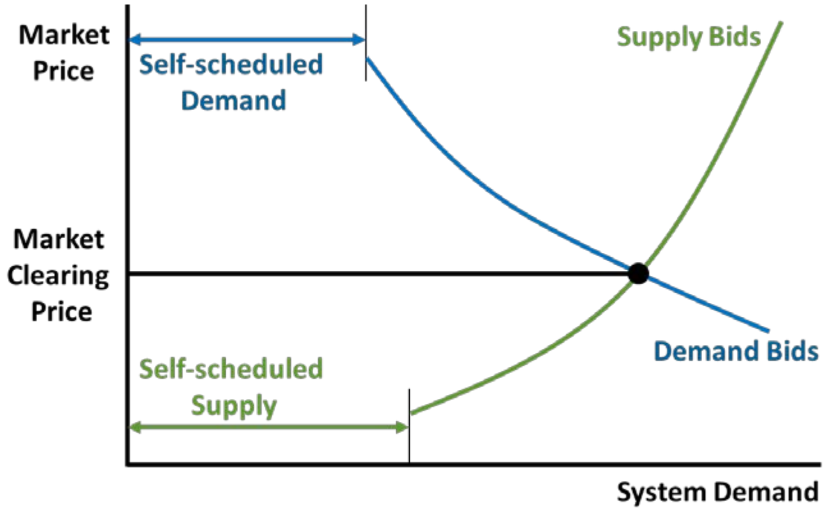


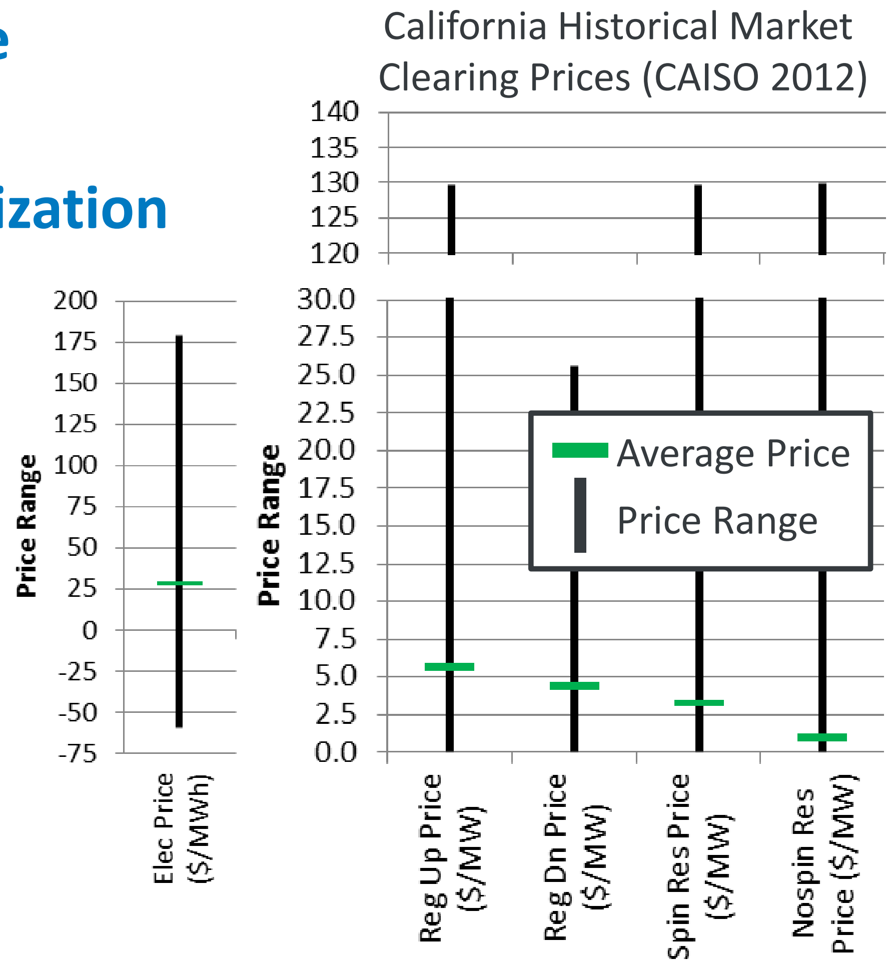
Source: Kirby, B.J. 2006. Demand Response for Power Systems Reliability: FAQ. ORNL

Objective #2

Assess the value proposition for grid integration of hydrogen technologies

- **Each market has different value and depth [4.5B]**
- **Need tool to perform co-optimization of all available services for H_2 technologies [4.5B,D]**



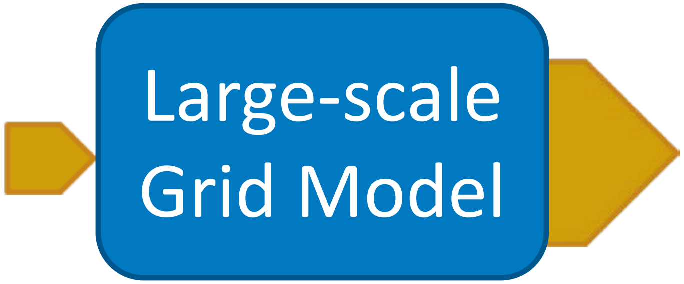


Objective #3

Include hydrogen technologies into large-scale grid operation models

- **Large-scale grid models are used for exploring the integration of renewables or alternative technologies**
  - 1,000's of generators and transmission lines
  - Performs mixed-integer optimization
  - Hourly or sub-hourly operation
- **Hydrogen has never been integrated into these models (e.g., PLEXOS, GridView, Concorda Maps) [4.5B,D]**

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



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

Electrolyzer Flexibility

Electrolyzer flexibility testing was performed to determine grid integration potential

- **Must consider the following characteristics for assessing grid integration potential [4.5A]**
  - Startup / Shutdown times
  - Minimum turndown
  - Response time
  - Ramp rate
  - Frequency response
- **Equipment tested at National Wind Technology Center (NWTC)**

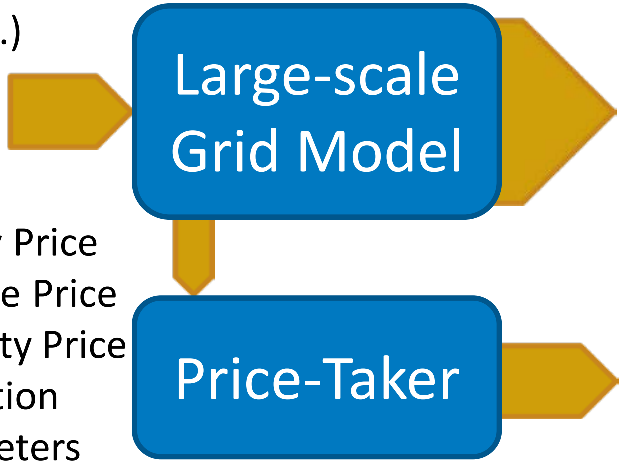
	PEM	Alkaline
Manufacturer	Proton OnSite	Teledyne Technologies
Electrical Power	50kW (208VAC)	40kW (480VAC)
Rated Current	155A per stack	220A 75 cell stack
Stack Count	3	1
Hydrogen Production	12 kg/day	13 kg/day
System Efficiency at Rated Current	68.6 (kWh/kg)	95.7 (kWh/kg)

Grid and Revenue Models

Models perform time-resolved optimization of electricity markets

- **The price-taker model (revenue model) can use historical data or large-scale grid model data for future scenarios (e.g., high renewable penetration)**
- **Price-taker calculates maximum revenue potential using market data and equipment operation parameters**

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



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

From grid model or historical data

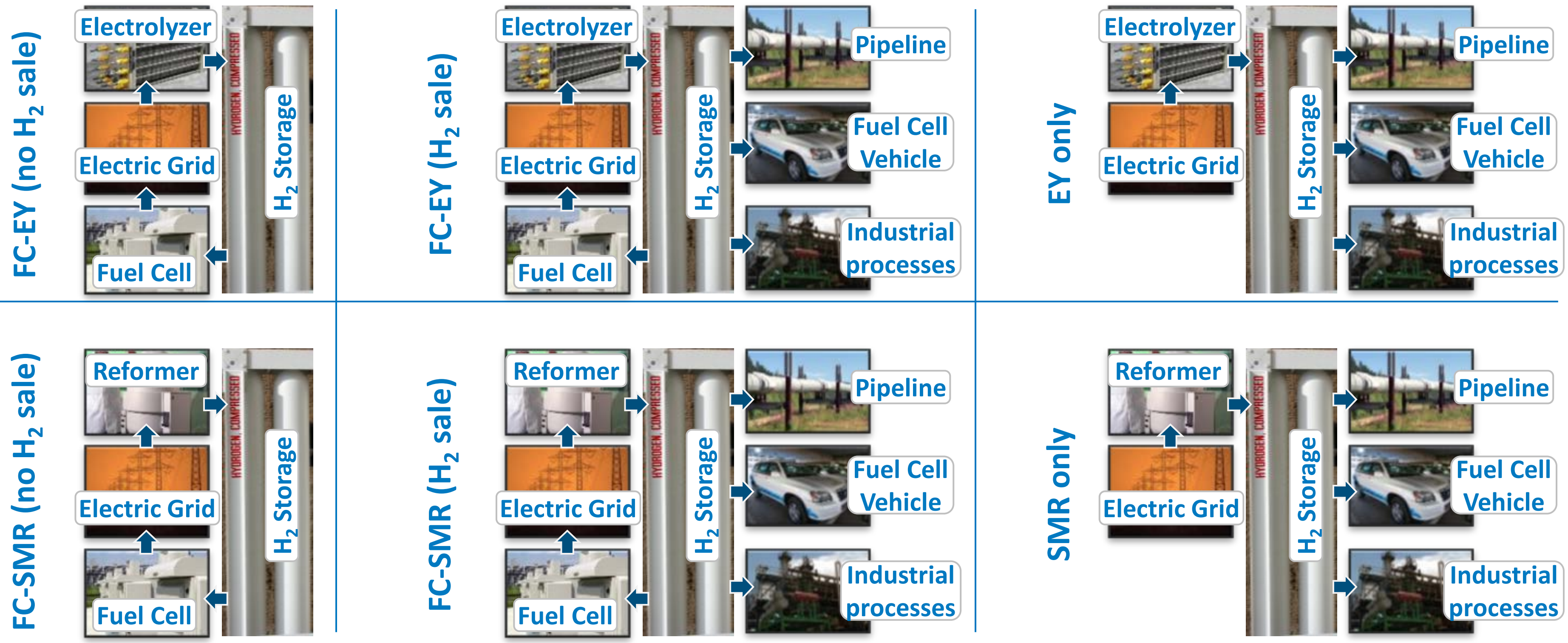
- Energy Price
- Reserve Price
- Capacity Price
- Operation Parameters

Profit based on operation (arbitrage, AS, H_2 sale, etc.)
(assumes devices don't impact the system)

Hydrogen system architectures

Hydrogen technology architectures can be flexible and many are examined for competitiveness

- Hydrogen analysis should include fuel cells (FC), electrolyzers (EY) and steam methane reformers (SMR)



Assumptions

Assumptions were selected to represent a range from the current (high cost) to future (low cost) values

- **Assumptions: Price-taker model**
  - Capacity market value is $150/kW-year
  - Sufficient capacity is available to participate in all markets
  - Devices don't impact market outcome (i.e., small compared to market size)

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

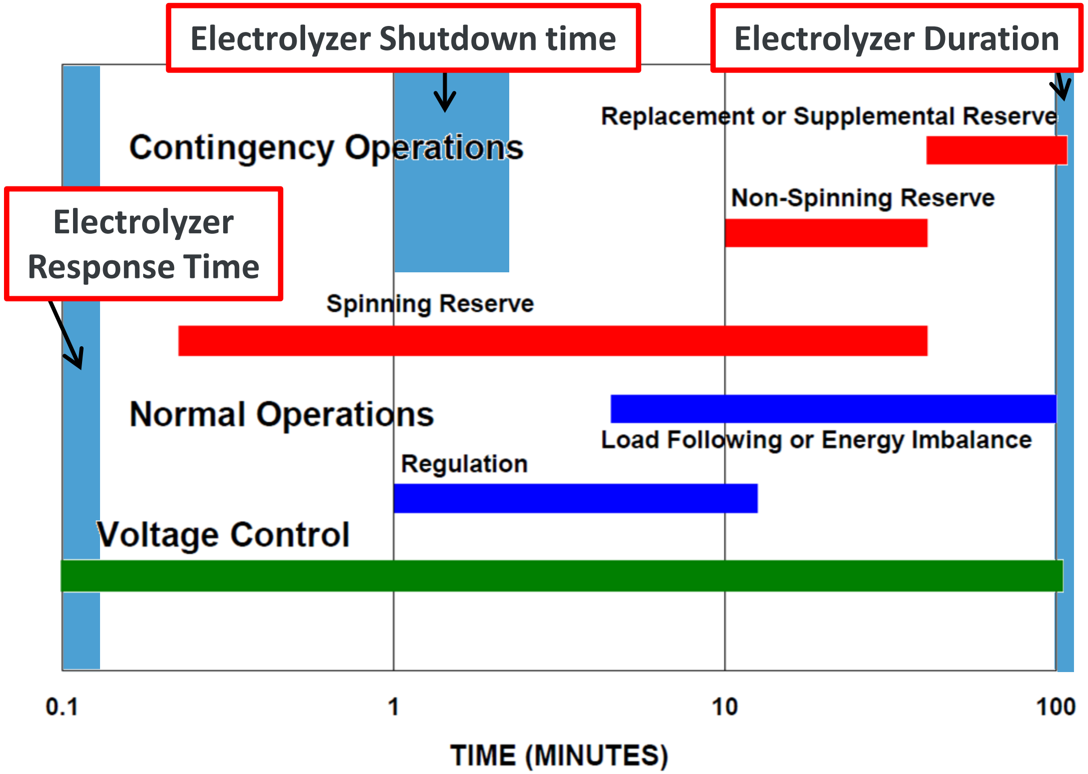
Properties	Pumped Hydro	Lead Acid Battery	Stationary Fuel Cell	Electrolyzer	Steam Methane Reformer
Rated Power Capacity (MW)	1.0	1.0	1.0	1.0	500 kg/day
Energy Capacity (hours)	8	4	8	8	8
Capital Cost ($/kW)	1500[1] - 2347[2]	2000[1] - 4600[1]	1500[3] - 5918[2]	430[3] - 2121[6]	427 – 569 $/kg/day[4]
Fixed O&M ($/kW-year)	8[1] - 14.27[2]	25[1] - 50[1]	350[2]	42[4]	4.07 – 4.50 % of Capital[4]
H_2 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)
[6]NREL 2008, NREL/TP-550-44103
[7]Levine, Jonah 2003, Michigan Technological University (MS Thesis)

Electrolyzer Flexibility

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

- **Electrolyzers can behave like demand response devices**
  - Startup and shutdown in minutes
  - Respond to a setpoint change in seconds
  - Can retain setpoint reduction for unlimited amount of time
    - Regulation up
    - Load-following up
    - Spinning Reserve
    - Non-Spinning Reserve
    - Replacement Reserve
- **Publishing NREL report with findings**



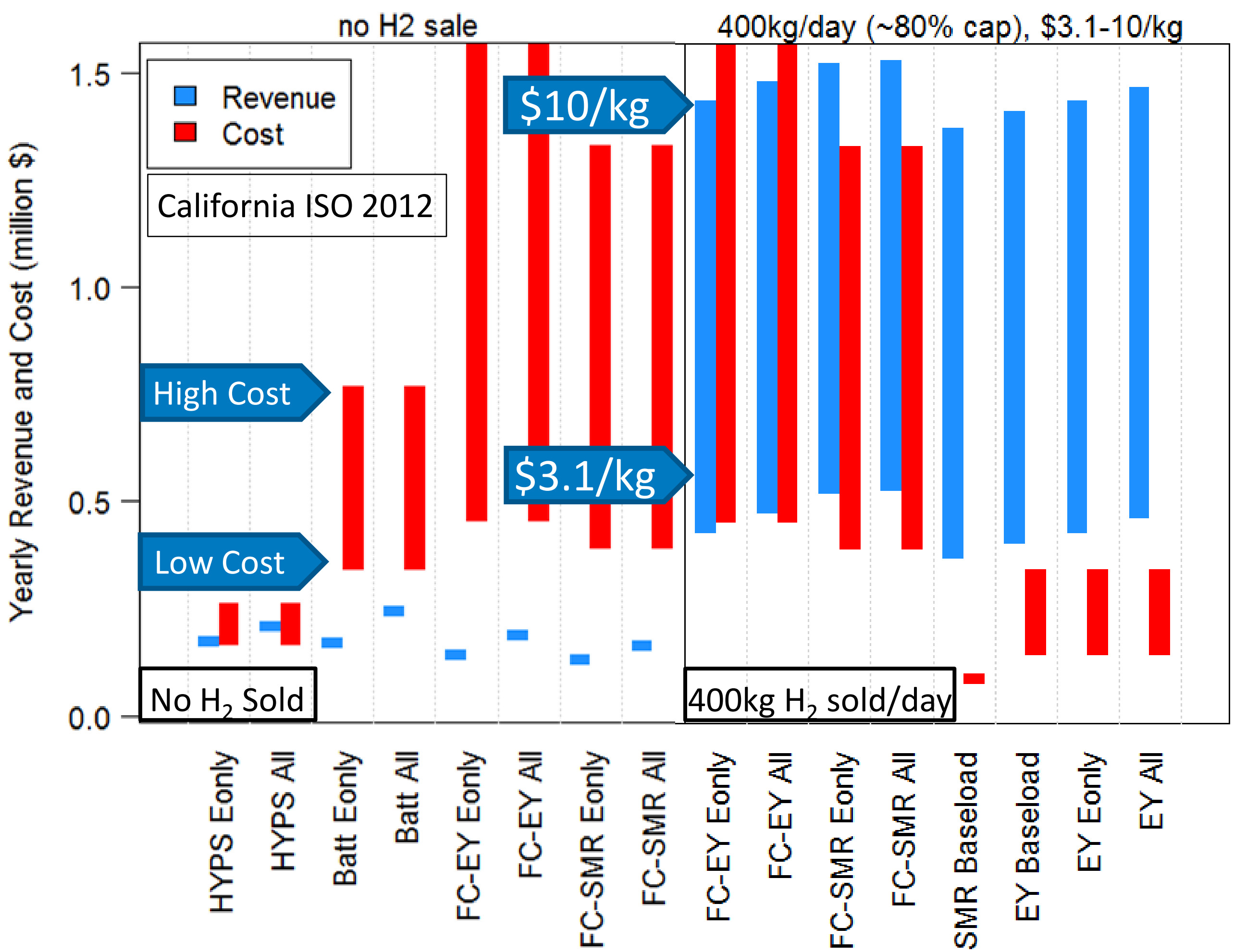
Source: Kirby, B.J. 2006. Demand Response for Power Systems Reliability: FAQ. ORNL
Source: Eichman, J.D.; Harrison, K.; Peters, M. (Forthcoming). Novel Electrolyzer Applications: Providing more than just Hydrogen. NREL/TP-5400-61758

Revenue Versus Cost Results

H_2 Storage devices that don't sell H_2 are not competitive

Providing ancillary services > Energy only > Baseload

Adding fuel cells can significantly increases costs



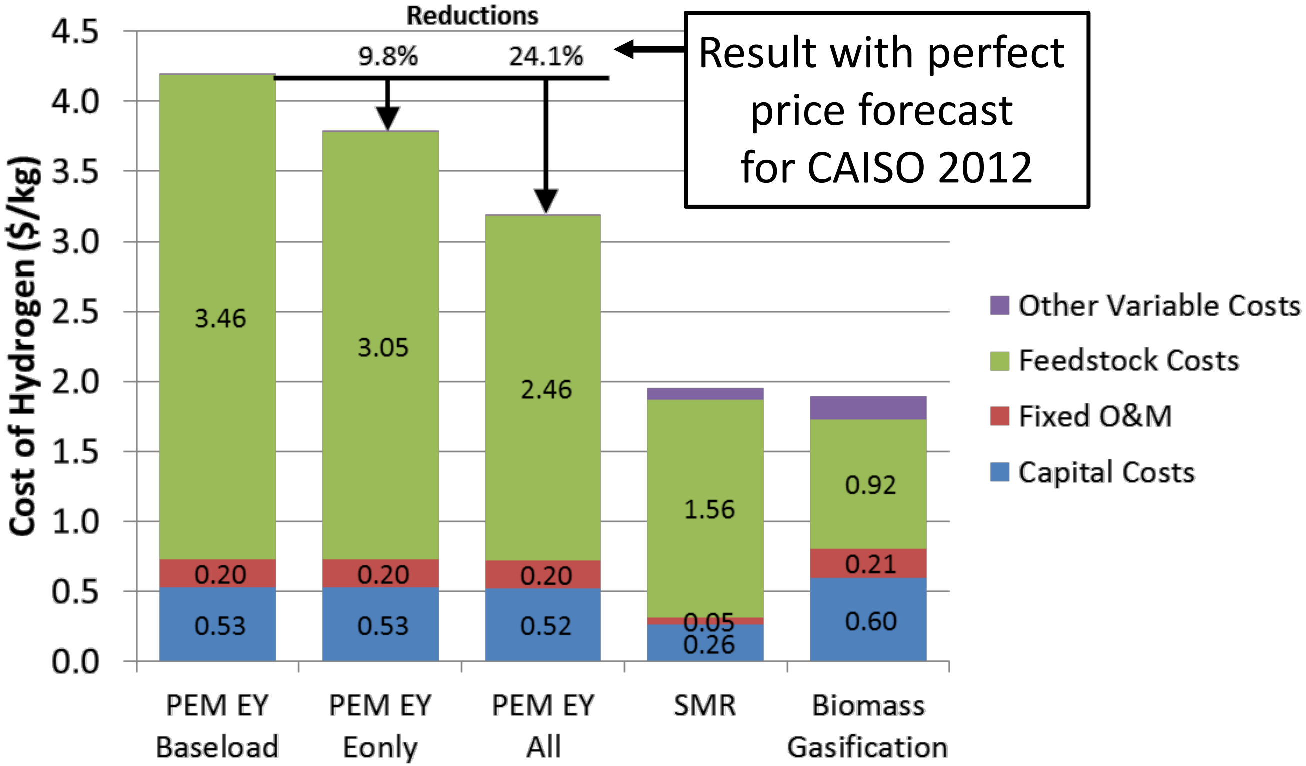
Name	Technology
HYPS	Pumped Hydro
Batt	Battery
FC	Fuel Cell
EY	Electrolyzer
SMR	Steam Methane Reformer

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

Comparison to H2A

Integration with the grid can lower feedstock costs

- **Future Central Hydrogen Production Scenarios with feedstock cost reductions from grid integration**



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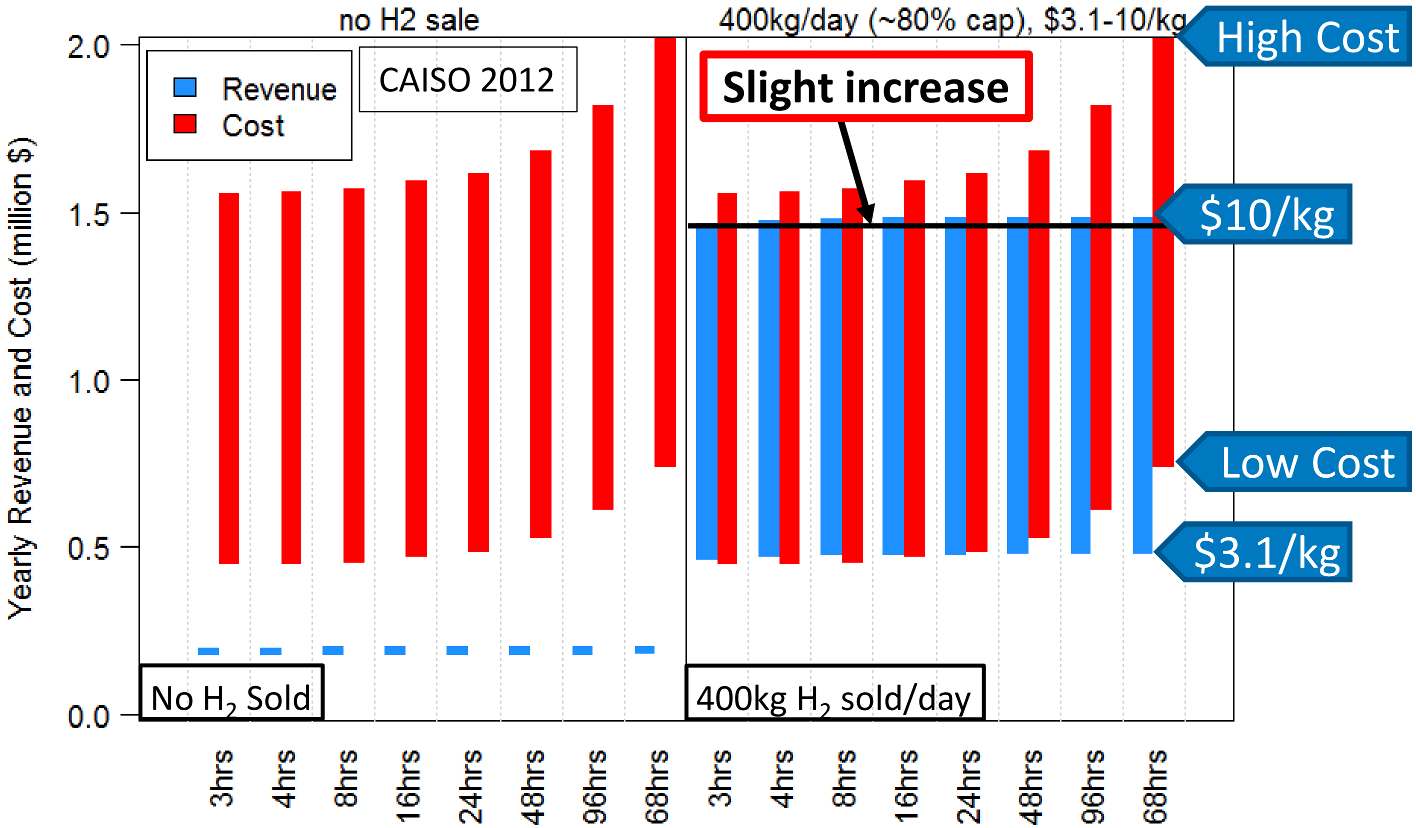
Storage Duration Sensitivity

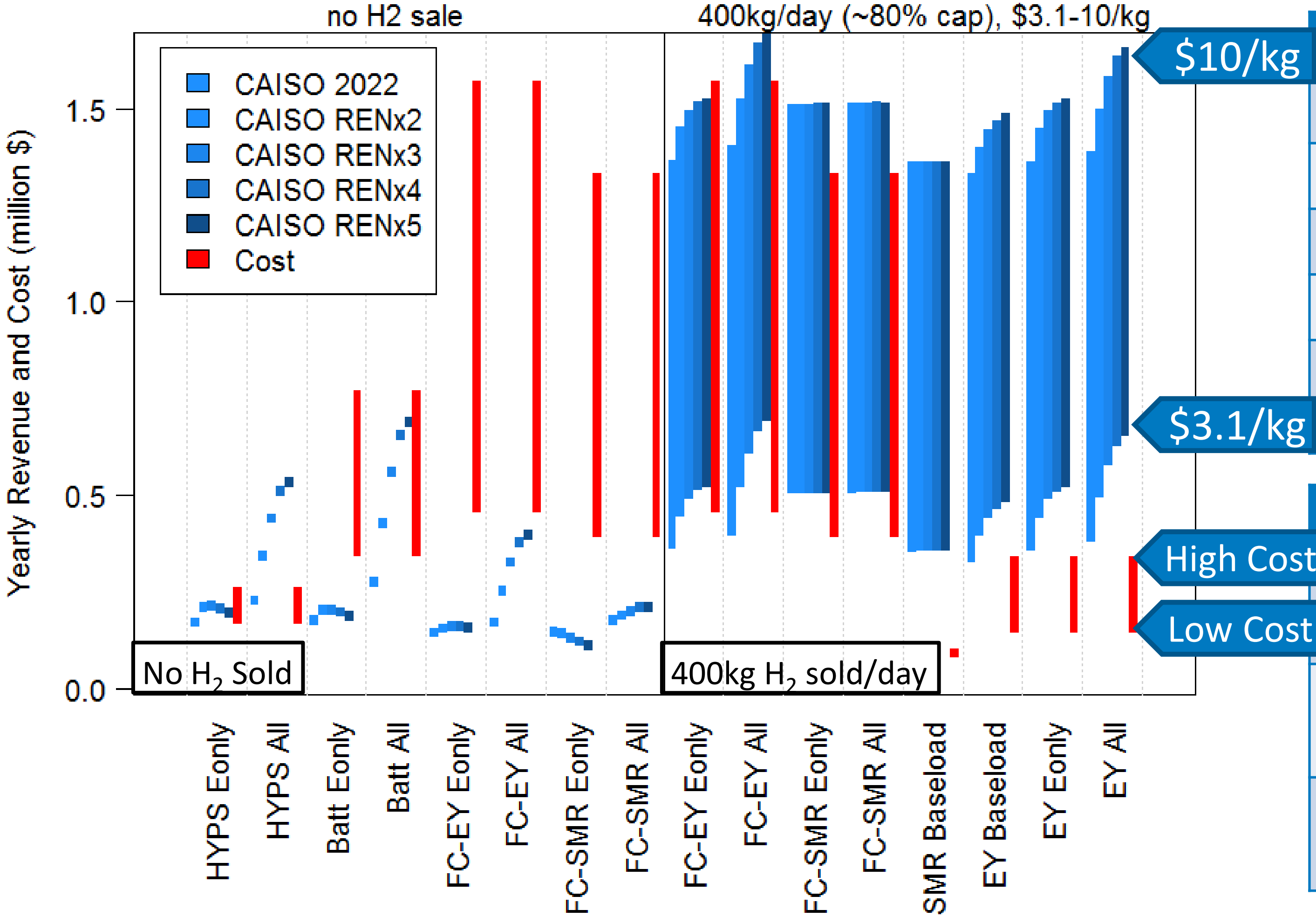
More storage duration is not necessarily more competitive in current energy and ancillary service markets

- Revenue versus cost comparison for FC-EY device with varying storage duration



Effect of increasing renewables

More renewables increases the value for devices participating in ancillary services and those selling H_2



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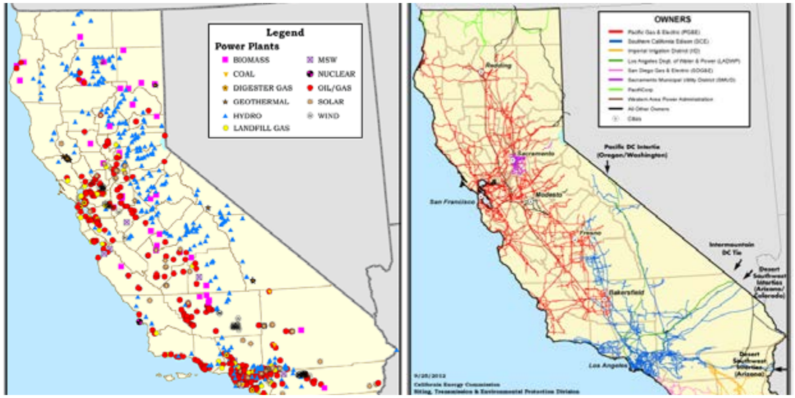
Electrolyzers in large-scale grid model

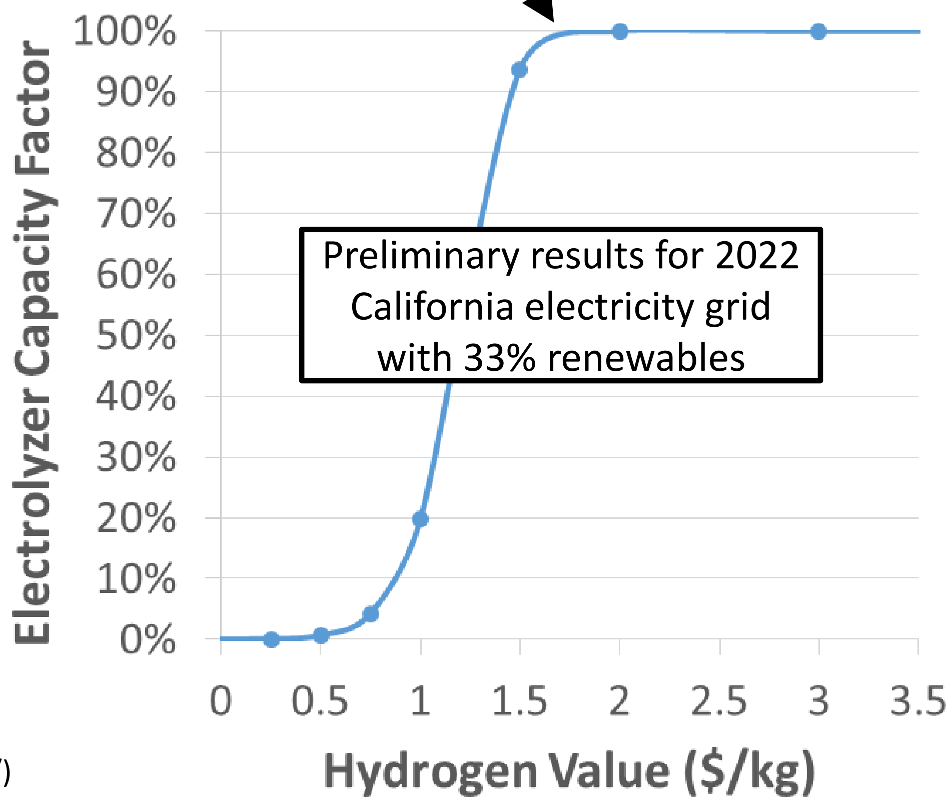
Successfully able to integrate H_2 technologies into a large-scale grid model

- **Integrating H_2 devices into the grid model shows how the grid will be affected [4.5B,D]**
  - Change in emissions?
  - Change in production cost?
  - Change generation mix?
  - Change prices?



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

Once the value of H_2 is high enough, sale of H_2 is more valuable than electricity (including arbitrage and ancillary services)



Previous Year Reviewers' Comments

No presentation for this project last year

Project Collaborations

Informed a variety of stakeholders about H_2 grid integration potential and received reviews to improve the analysis

- **This work was presented to a variety of industry and government stakeholders to inform them of H_2 grid integration potential and to receive reviews to improve the assumptions and results.**
- **Interactions / Reviewers**
    - Xcel Energy
    - FuelCell Energy
    - Versa Power
    - ITM Power
    - Proton Onsite
    - DOE Fuel Cell Technology Office
    - NREL

Challenges and Barriers

- **Need to disseminate findings to hydrogen community as well as utilities, grid operators, etc.**
- **Policy or regulatory hurdles hindering integration of hydrogen technologies into the grid**
  - Capacity requirements (>1MW)
  - Interaction with multiple markets (i.e., electricity, gas, transportation)

Proposed Future Work

- Complete publication of electrolyzer flexibility paper
- Submit paper with price-taker analysis results to peer-reviewed journal
- Run large-scale grid model with different H_2 technology configurations

Summary

This work explores future market opportunities for H_2 technologies and expands modeling capabilities for integration with the grid

- **Electrolyzers are flexible enough to participate in energy and ancillary service markets [4.5A]**
- **Enabling H_2 technologies to integrate with electricity markets can enhance the value proposition [4.5B,D]**
  - Sell H_2: FC-EY systems providing strictly storage are less competitive than systems that sell H_2 (use of curtailed energy can affect outcome)
  - Revenue w/ ancillary service > energy only > baseload
  - Electrolyzers operating as a "demand response" devices have very favorable prospects
  - More storage is not necessarily more competitive in current energy and ancillary service markets (but may add value in capacity market)

Technical Back-Up Slides

Acronyms

- **Acronyms**
  - AC — Alternating current
  - AS — Ancillary Services
  - CAISO — California Independent System Operator
  - NYISO — New York Independent System Operator
  - ISO-NE — Independent System Operator, New England
  - EY — Electrolyzer
  - FC — Fuel Cell
  - HYPS — Hydroelectric pumped storage
  - kg — Kilogram
  - kWh — Kilowatt-hour
  - LHV — Lower heating value
  - MMBTU — Million British thermal units
  - O&M — Operation and maintenance
  - SMR — Steam Methane Reformer

Price-Taker Model

Performs time-resolved co-optimization of electricity markets (energy and ancillary service products)

- **Price-Taker model calculates maximum revenue potential using market data and equipment operation parameters**
  - Energy Prices (e.g., hourly CAISO 2012)
  - Reserve Prices (e.g., hourly CAISO 2012)
  - Capacity Price (for new market entry)
  - Hydrogen Prices (Sensitivity performed)
  - Operation Parameters (e.g., power, efficiency, capacity, availability)

Price-Taker Co-optimization Model

Profit based on operation (arbitrage, ancillary services, etc.)

Assumptions

1.) Sufficient capacity is available in all markets

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

3.) Capacity market value is $150/kW-year

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

Electrolyzer testing

Electrolyzers can respond sufficiently quick enough to participate in frequency regulation

- Response time and ramp-rate tests were performed for the electrolyzers