



PG&E H2@Scale CRADA: Optimizing an Integrated Solar-Electrolysis System

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March 1, 2018

Outline

- NREL Team
- Goal and objectives
- Project Team and Roles
- Tasks and schedule
- Deliverables
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- Approach

NREL Team

Sustainable Transportation
- Vehicle Technologies
- Hydrogen
- Biofuels

Energy Productivity
- Residential Buildings
- Commercial Buildings
- Manufacturing

Renewable Electricity
- Solar
- Wind
- Water: Marine Hydrokinetics
- Geothermal

Systems Integration
- Grid Integration of Clean Energy
- Distributed Energy Systems
- Batteries and Thermal Storage
- Energy Analysis

Partnerships
- Private Industry
- Federal Agencies
- State/Local Government
- International

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Goal and Objectives

Goal

Model and evaluate an optimized integrated renewable-electrolysis system to establish the potential benefits and facilitate broader adoption.

Objectives

1. Holistically model various value streams created by an integrated solar power – electrolyzer system that produces hydrogen for use in the transportation sector
2. Design an optimized integrated renewable power – electrolyzer system (solar power plant, electrolyzer, and hydrogen storage)

The value streams that we will model are:

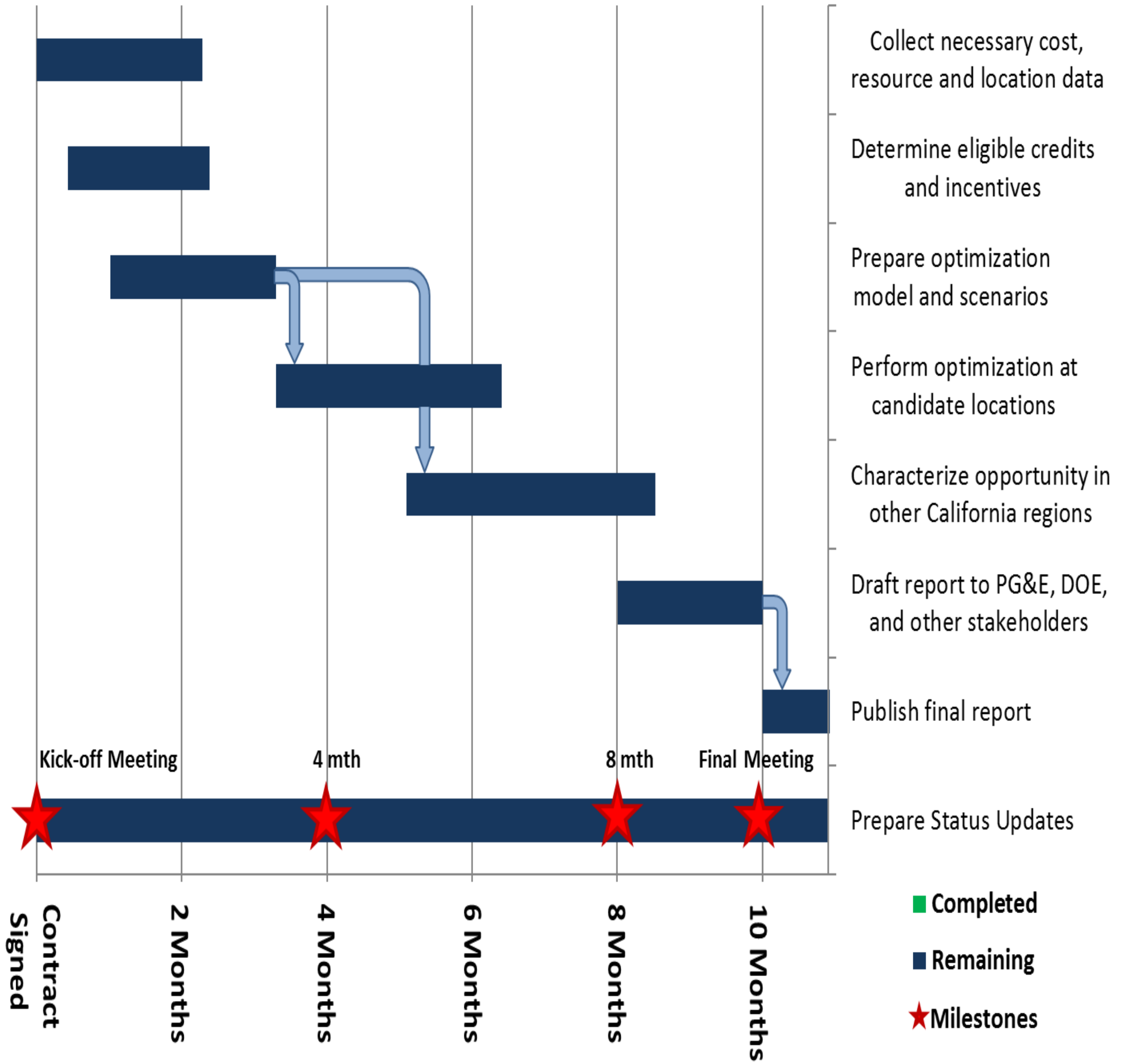
- Power sold from the renewable plant into the grid
- Ancillary services provided by the renewable plant which the electrolyzer enables
- Reduced need for reserves and flexibility to support the intermittent solar resource
- Net value of hydrogen produced
- Additional credit and incentive value from the production of a low carbon fuel

Project Team and Roles

- Pacific Gas & Electric Corporation
  - Project Management
  - Feedback on PG&E needs and market opportunities and constraints
  - Critical review
- National Renewable Energy Laboratory
  - Modeling and analysis
  - Interim progress presentations and reporting
  - Draft and final report
- California Air Resources Board
  - New LCFS pathways
  - Value of incentives and credits
  - Understanding emissions reduction potential for solar-electrolysis systems (compare to PV alone)
  - Critical review
- California Governor's Office of Business and Economic Development
  - Current opportunities for solar-electrolysis providers (e.g., project financing, incentives)
  - New strategies to encourage business activity in the solar-electrolysis space
  - Critical review

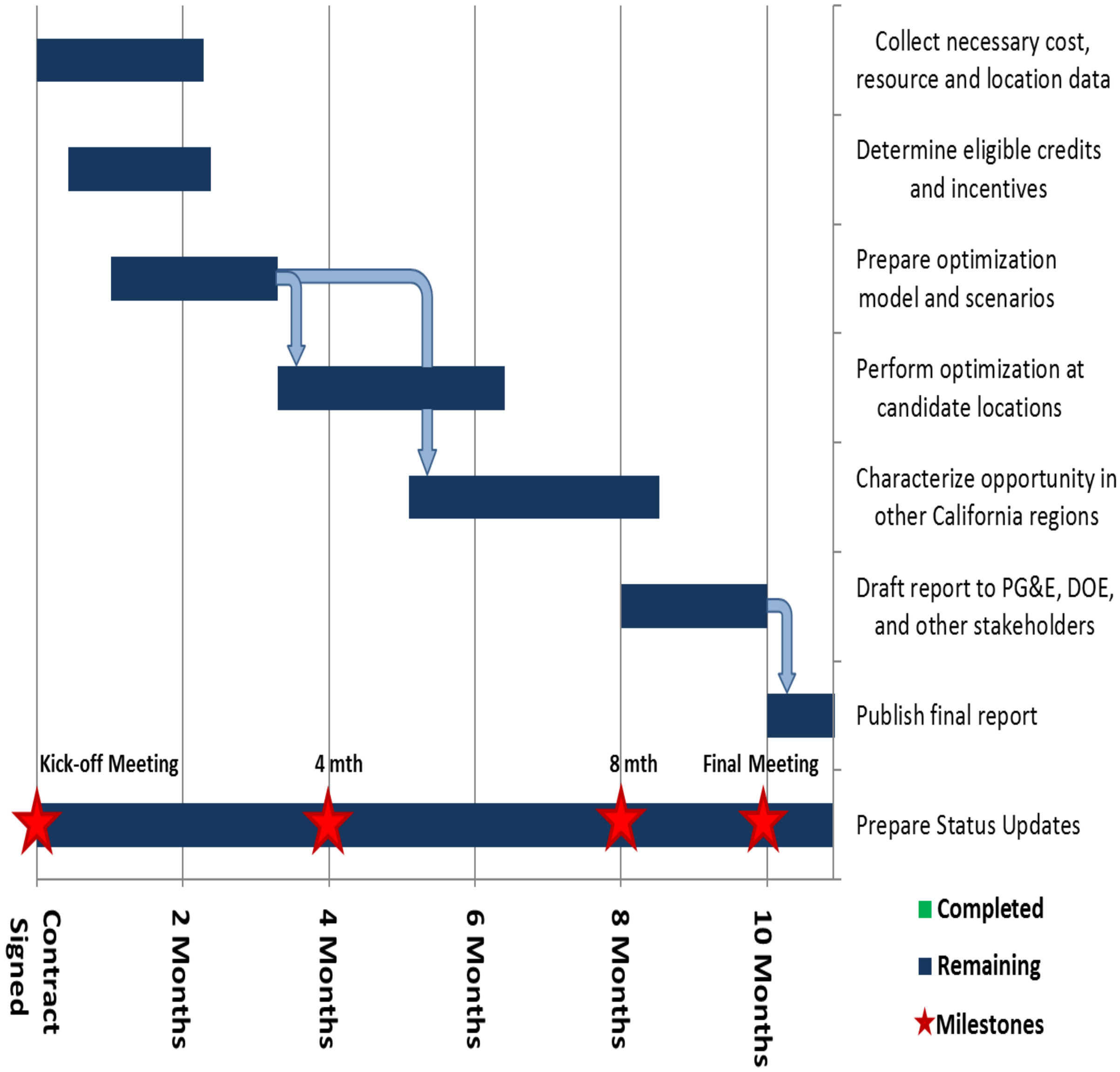
Tasks and Schedule

Task	Description
1.0	Data collection
1.1	• Collect necessary location, cost and resource data
1.2	• Determine eligible credits and incentives
2.0	Perform optimization
2.1	• Prepare optimization model to integrate PV and electrolysis and setup desired scenarios
	• Perform integrated solar-electrolysis optimization at



Deliverables

1. **Kick-off meeting**
2. **Monthly progress update**
3. **Presentation of interim results (every 4 months)**
4. **Draft report and worksheets for review**
5. **Presentation of final results**
6. **Final report and worksheets**

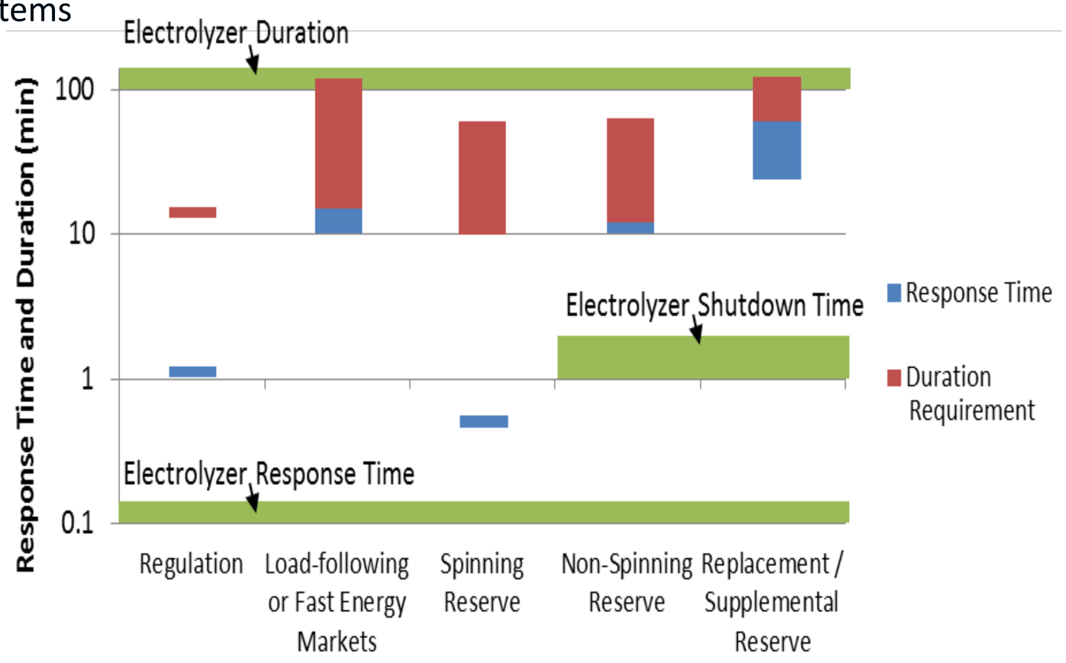


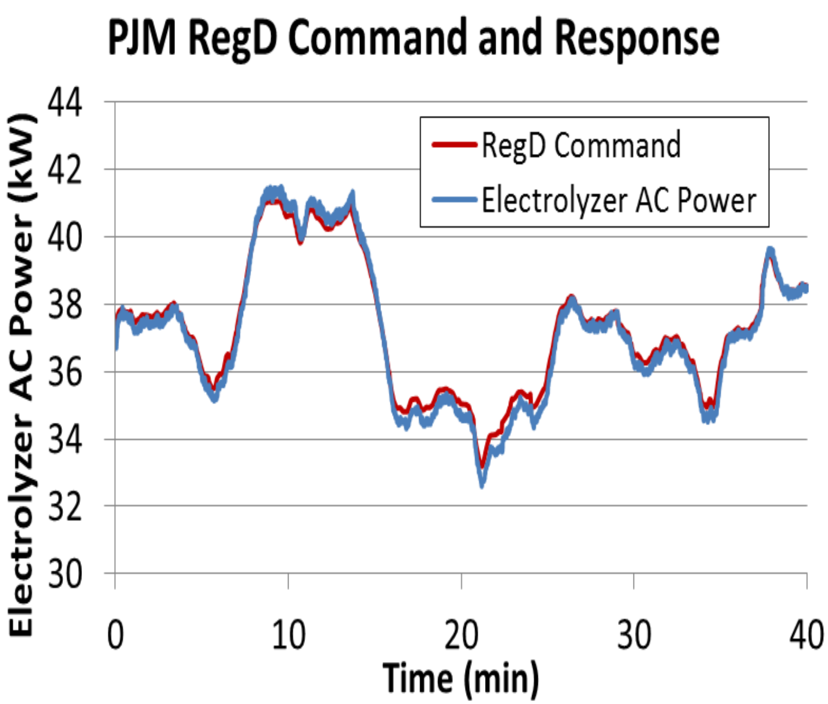
Previous Studies

Electrolyzer Flexibility Testing

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

Source: Kirby, 2006. Demand Response for Power Systems Reliability: FAQ
Source: Eichman, 2014 (www.nrel.gov/docs/fy14osti/61758.pdf)



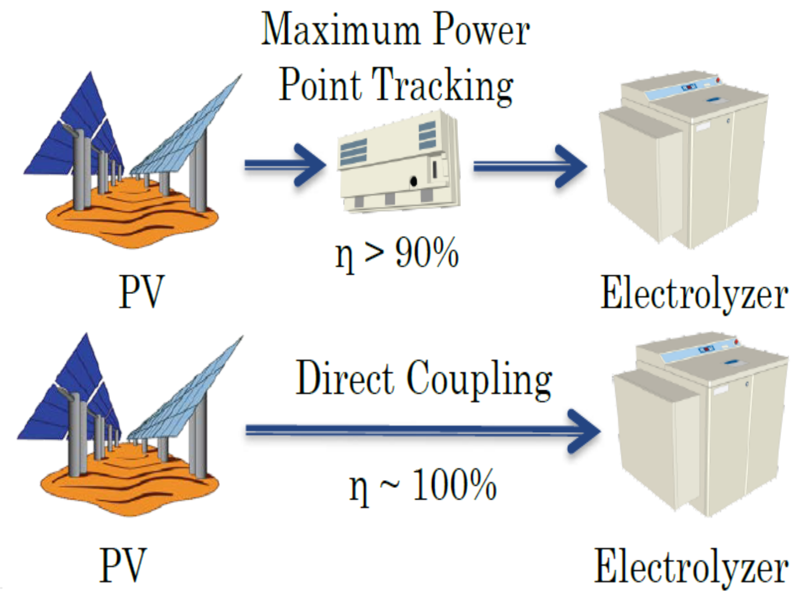


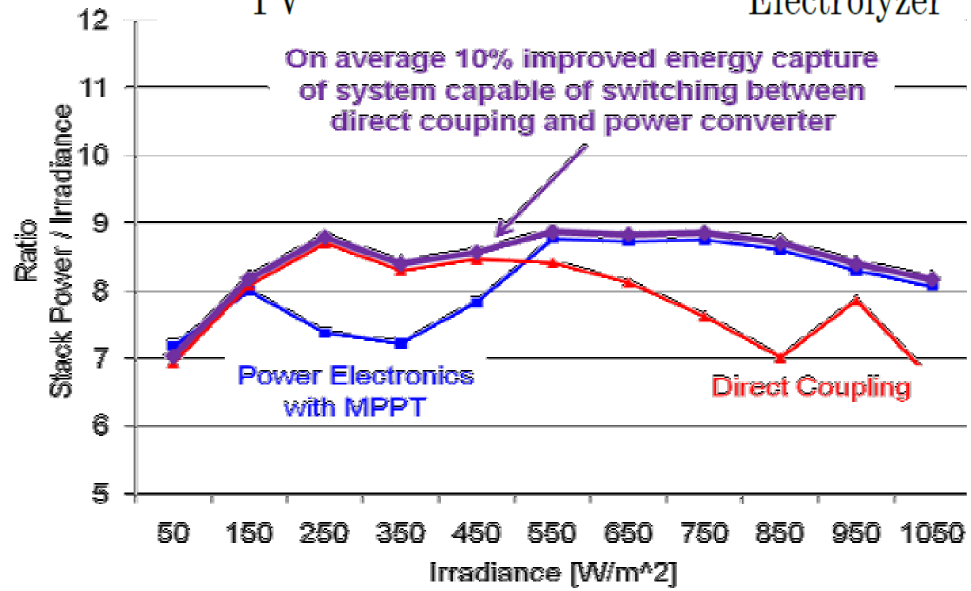
- Validated electrolyzer stack response to regulation signal
- Electrolyzers can respond to regulation signals and accelerate frequency recovery

Source: Peters, M., NREL 2014

Renewable Electrolysis Integrated System Design and Testing

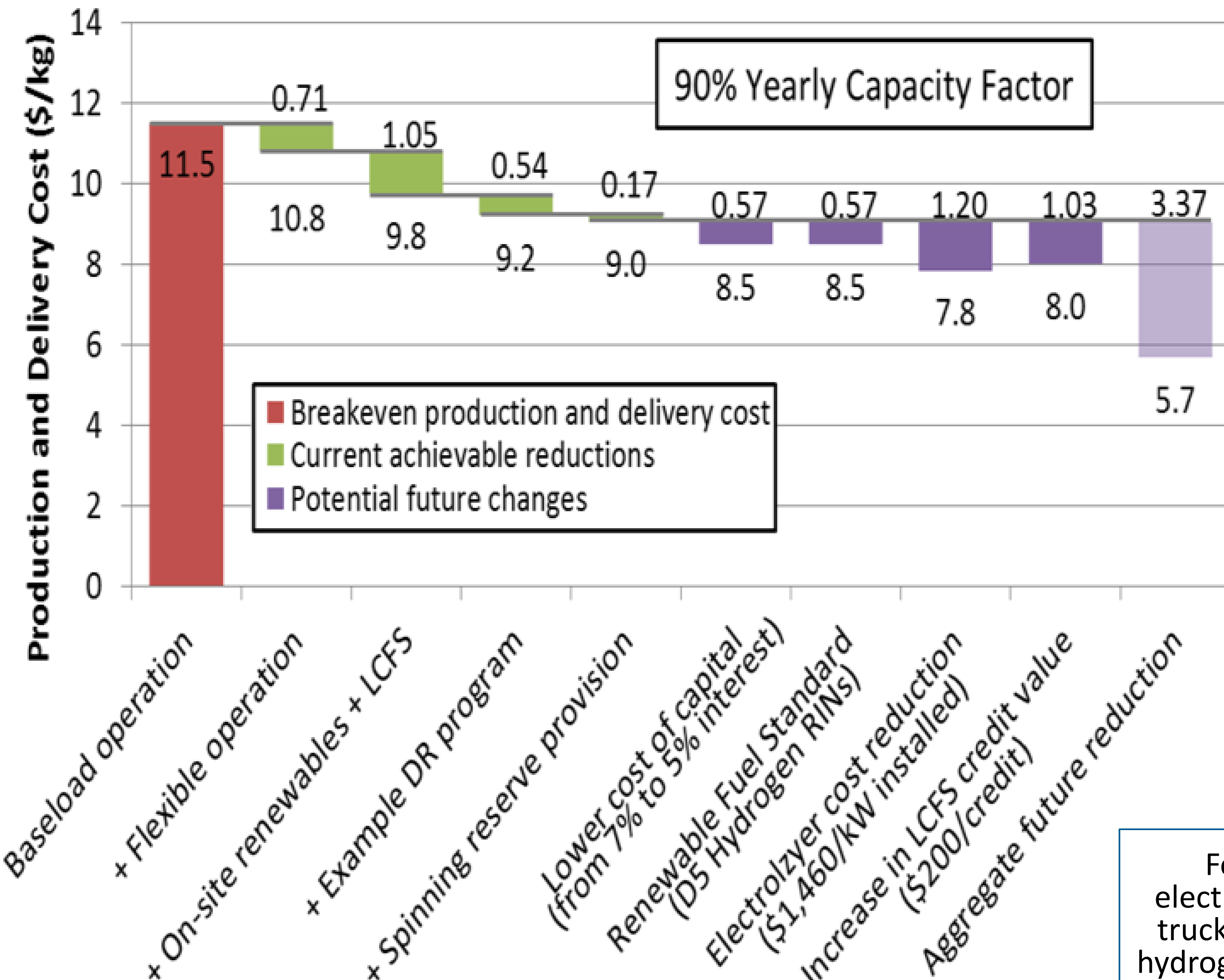
- NREL has tested direct coupling of wind and PV with electrolysis equipment
- PV shows efficiency improvements beyond conventional maximum power point tracking





Source: Peters, 2017 (w.hydrogen.energy.gov/pdfs/review17/pd031_peters_2017_o.

CARB-DOE P2G/P2H Business Case Study (December 2016)



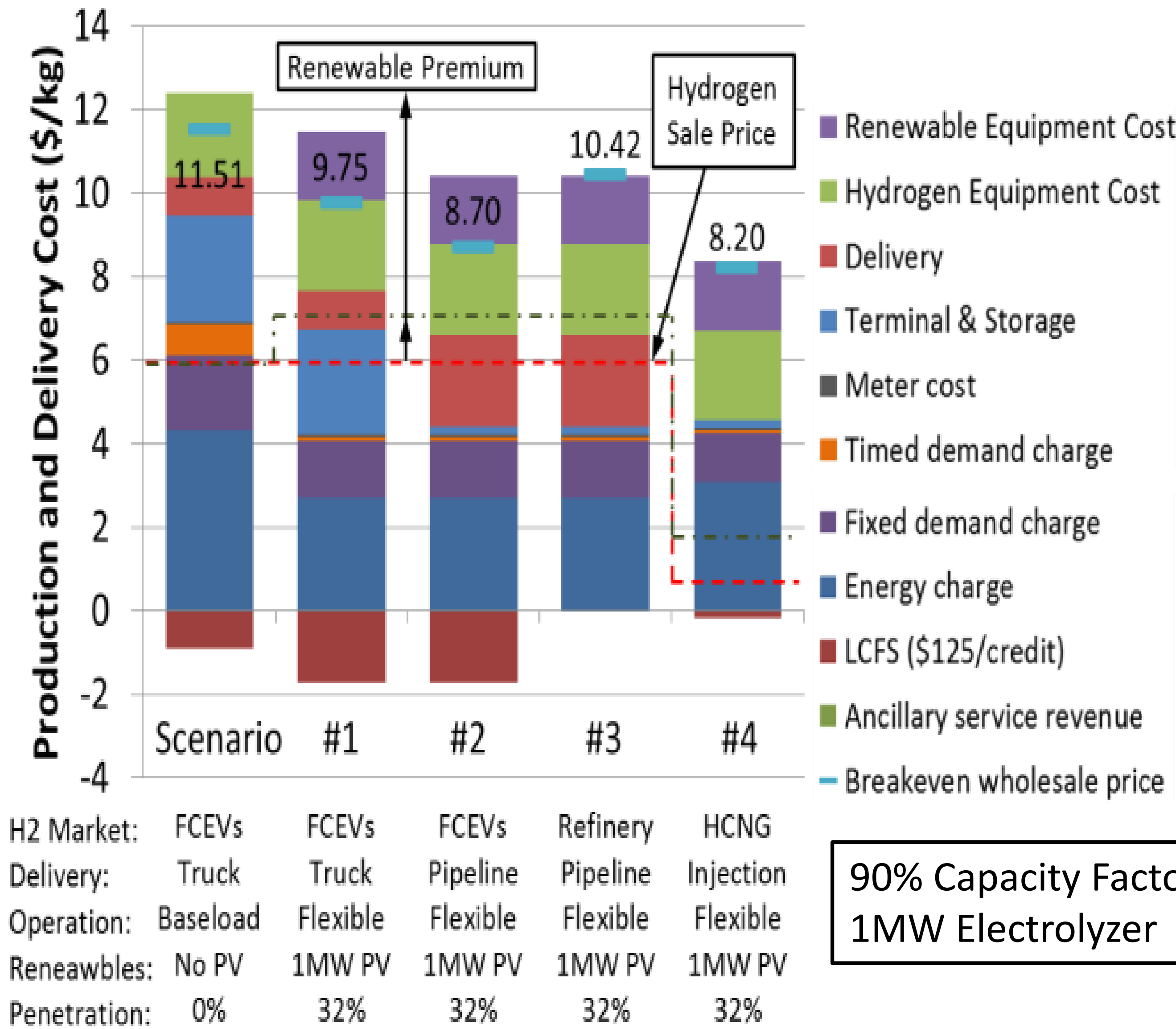
For 1MW electrolyzer with truck delivery of hydrogen for FCEVs

Source: Eichman, J., Flores-Espino, F., (2016).

www.nrel.gov/docs/fy17osti/67384.pdf

CARB-DOE P2G/P2H Business Case Study (December 2016)

- The addition of on-site renewables reduces all energy cost components and is even valuable without the LCFS.
- Scenario 1 and 2 are the most compelling because of the LCFS for FCEVs.
- Pipeline delivery is cheaper but can vary significantly based on location compared to truck delivery.



90% Capacity Facto
1MW Electrolyzer

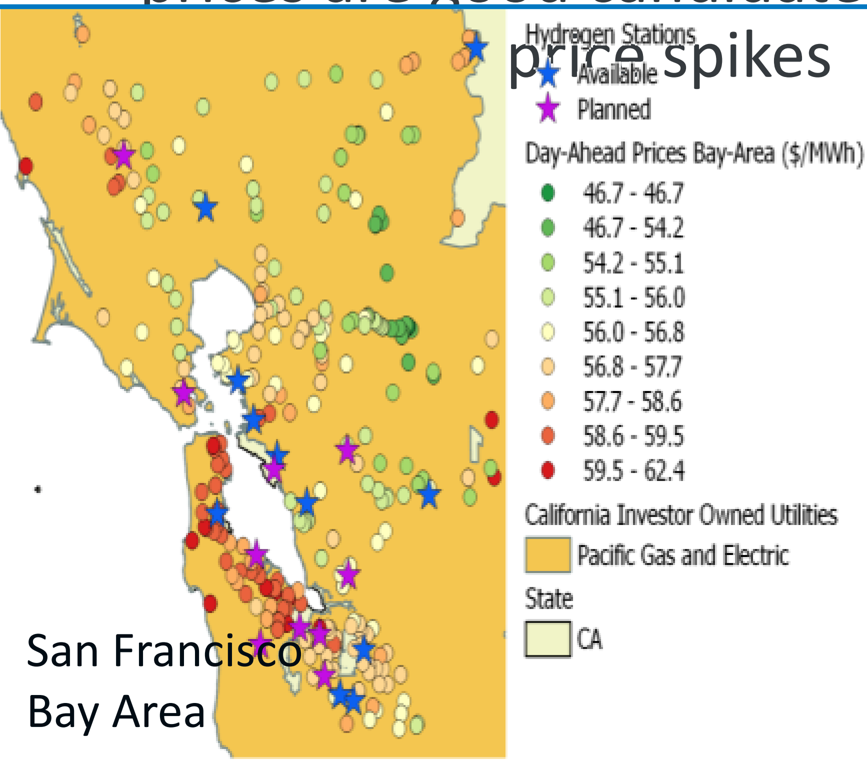
Source: Eichman, J., Flores-Espino, F., (2016). www.nrel.gov/docs/fy17osti/67384.pdf

CARB-DOE P2G/P2H Business Case Study (December 2016)

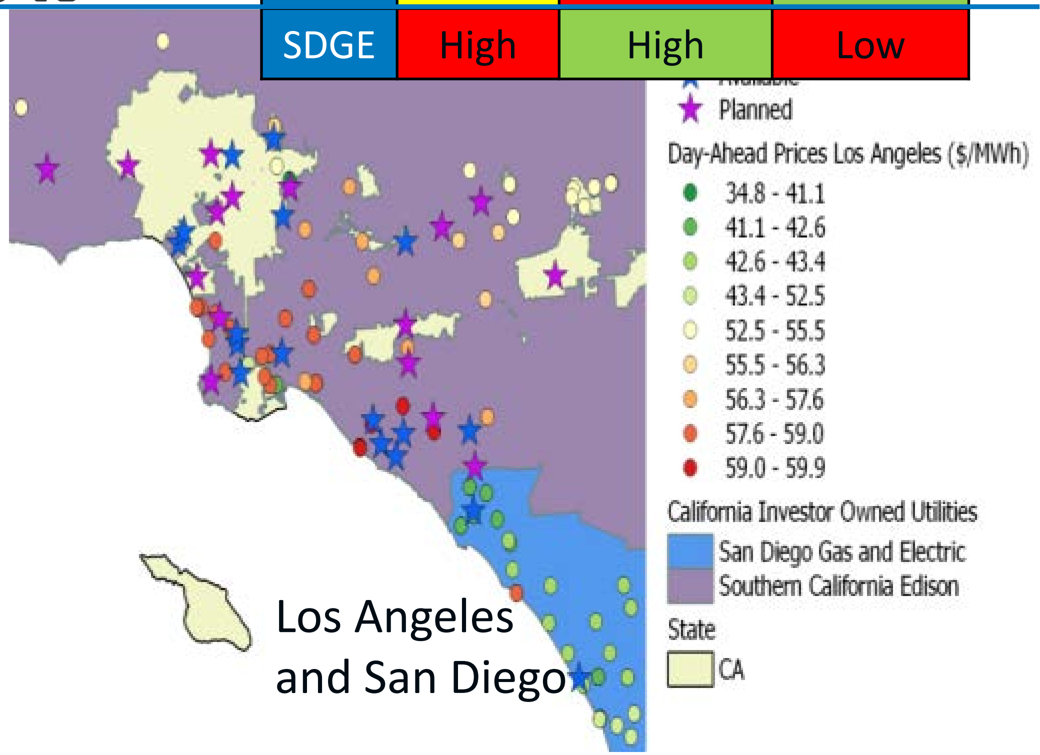
- Currently, energy market value comes from reducing demand during price spikes
- Areas with high average energy prices are good candidates to price spikes

Summary

Utility	Utility Rates	Ancillary Service Value	Average Energy Price
SCE	Low	High	High
PG&E	Medium	Low	High
SDGE	High	High	Low



San Francisco Bay Area



Los Angeles and San Diego

Source: Eichman, J., Flores-Espino, F., (2016). www.nrel.gov/docs/fy17osti/67384.pdf

Fuel Cell and Hydrogen Joint Undertaking (FCH-JU) P2H Business Cases (June 2017)

- Identify early business cases and assess their potential replicability within the EU from now until 2025.
- Identify particular sub-national locations where low-cost electricity is available based on electricity market and transmission grid models.

WACC on CAPEX: 5% Project lifetime: 20 years	SC mobility (Albi, France)		Food industry (Trige, Denmark)		Large industry (Lubeck, Germany)	
	2017	2025	2017	2025	2017	2025
Primary market H2 volume (t/year)	270	950	900	900	3 230	3 230
Average total electricity price for prim. market (€/MWh)	44	45	38	47	17	26
Net margin without grid services (k€/MW/year)	39	71	228	248	-146	30
Net margin with grid services (k€/MW/year)	159	256	373	393	-13	195
Share of grid services in net margin (%)	75%	72%	39%	37%	-	85%
Payback time without grid services (years)	11.0	9.0	4.6	3.7	-	8.4
Payback time with grid services (years)	8.0	4.5	3.4	2.7	-	3.5
Key risk factors	• Taxes & Grid fees • H2 price • Size of fleets • Injection tariff • FCR value		• H2 price • Taxes & Grid fees • FCR value		• Taxes & Grid fees • FCR value • Carbon price	

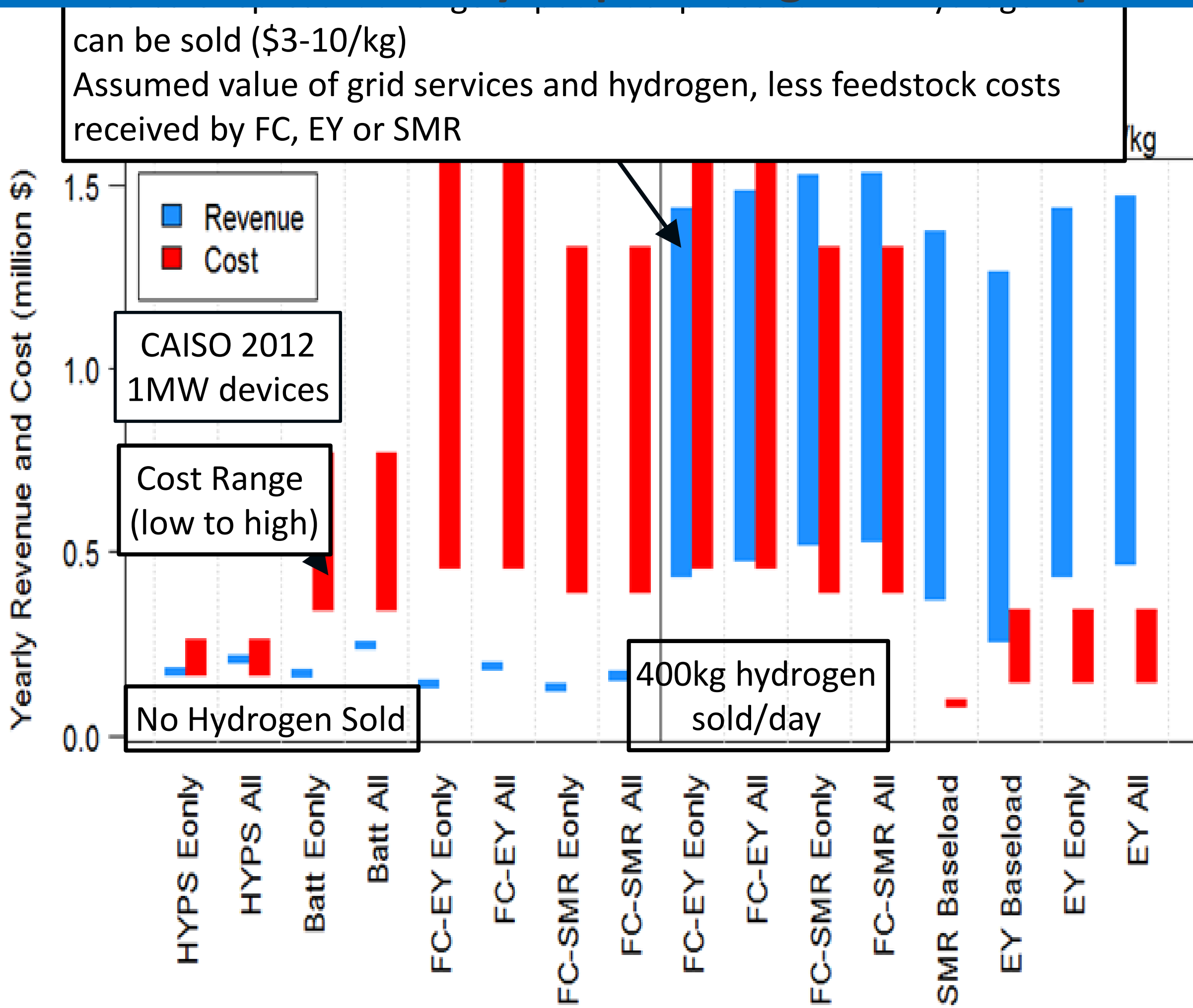
Source: FCH-JU 2017 (www.fch.europa.eu/sites/default/files/P2H_Full_Study_FCH

Wholesale market value (energy and ancillary services) (2016)

Selling hydrogen increases competitiveness

Providing ancillary services > Energy only > Baseload

Electrolyzer providing demand response is promising



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

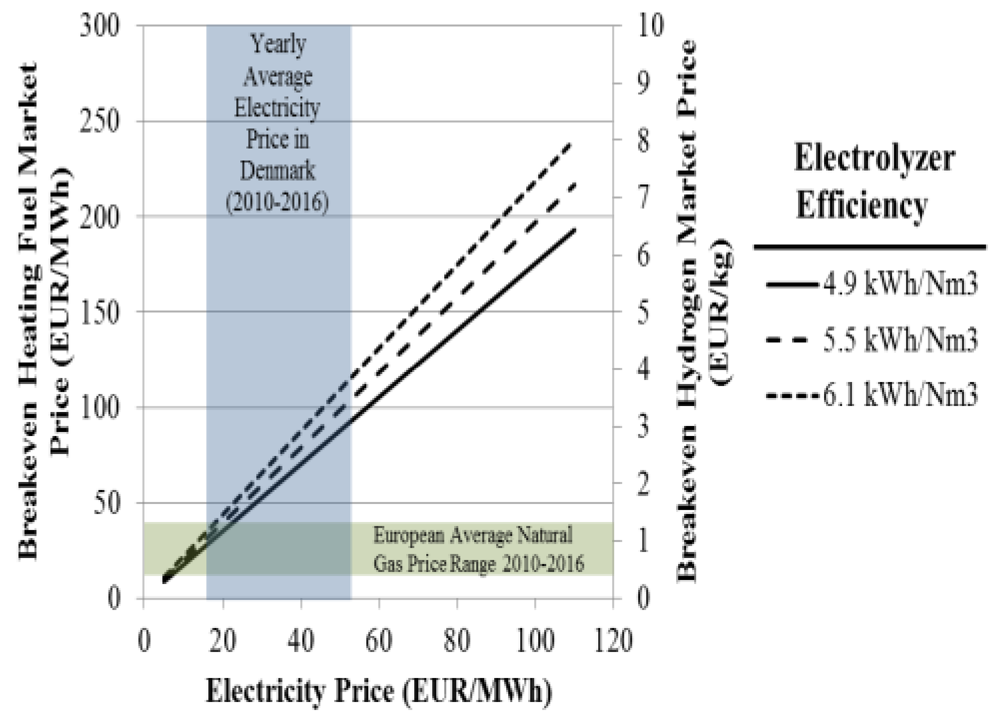
Name	Services
All	All Ancillary Services
Eonly	Energy Arbitrage only
Baseload	“Flat” operation

Source: Eichman, J., Townsend, A., Melaina, M., 2016. www.nrel.gov/docs/fy16osti/65856.pdf

Optimizing Wind-Electrolytic Hydrogen Systems in Denmark (2017)

Summary

- Benefits of integration of offshore wind and electrolysis are captured in terms of a return on investment
- The paper examines wholesale prices in the Danish electricity system
- Tradeoffs between selling hydrogen to customers or regenerating electricity are explored
- The most beneficial configuration is to produce hydrogen to complement the wind farm and sell directly to end users

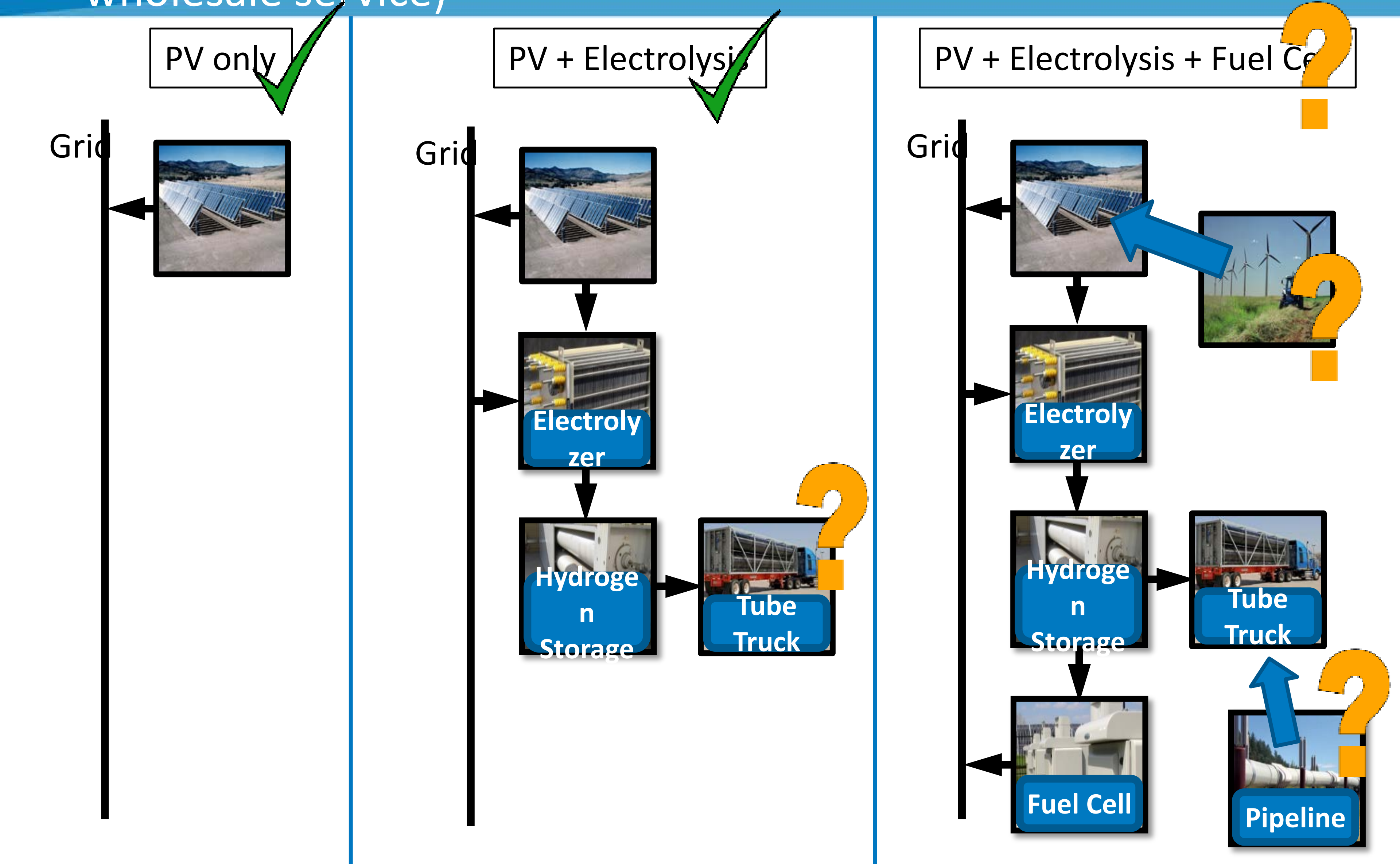


	Return on Investment (year)	Total benefits in NPV (M€/yr)	Hydrogen price (€/kg)
Benchmark	/	4.15	/
Scenario I	Inf	4.15	0
Scenario II	24.4	4.61	2
Scenario III	5.5	7.02	5
Scenario IV	2.6	13.13	9

Source: Hou et al., 2017. Optimizing investments in coupled offshore wind-electrolytic hydrogen storage systems in Denmark, Journal of Power Sources, 359: 186-197.

Approach

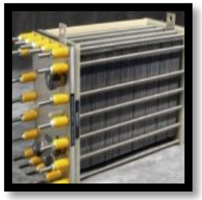
Equipment Configuration (all systems have access to wholesale service)



Source: Matt Stiveson, NREL 12508; Keith Wipke, NREL 17319; NextEnergy Center, NREL 16129; ENTECH, NREL 03657; Lincoln Composites, NREL 22261

Value Streams

- Photovoltaic
  - Incentives and credits
  - Sale of electricity
  - Renewable credits



- Electrolysis
  - Incentives and credits
  - Sale of hydrogen
  - Grid services (e.g., energy, capacity, ancillary services)
  - Smooth photovoltaic supply

- Fuel Cell
  - Incentives and credits
  - Sale of electricity
  - Grid services (e.g., energy, capacity, ancillary services)
  - Smooth photovoltaic supply

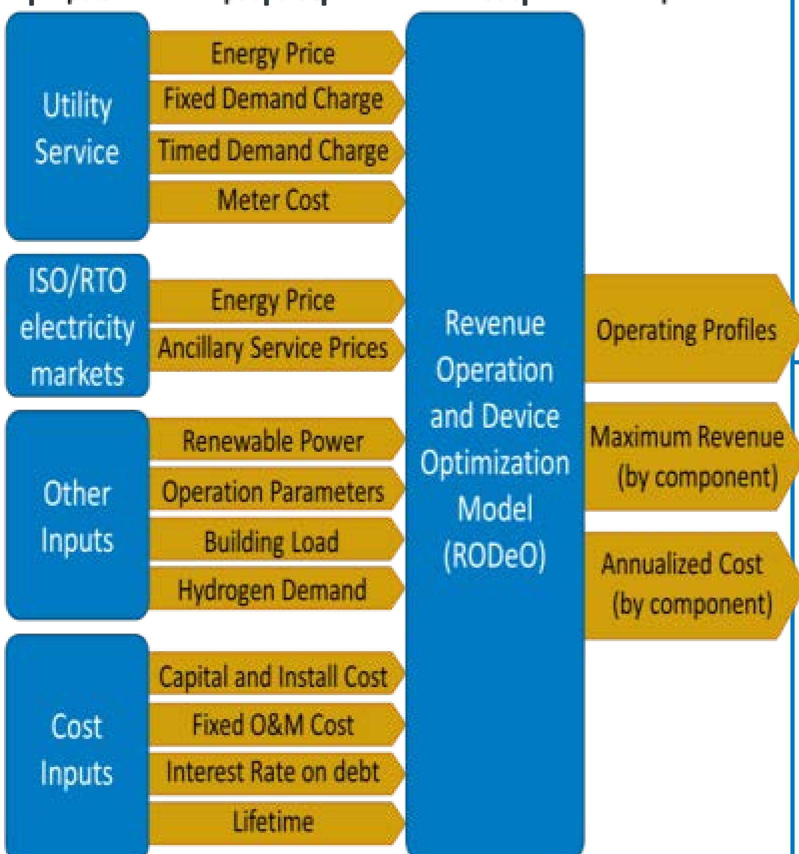
Source: Matt Stiveson, NREL 12508; Keith Wipke, NREL 17319; ENTECH, NREL 03657

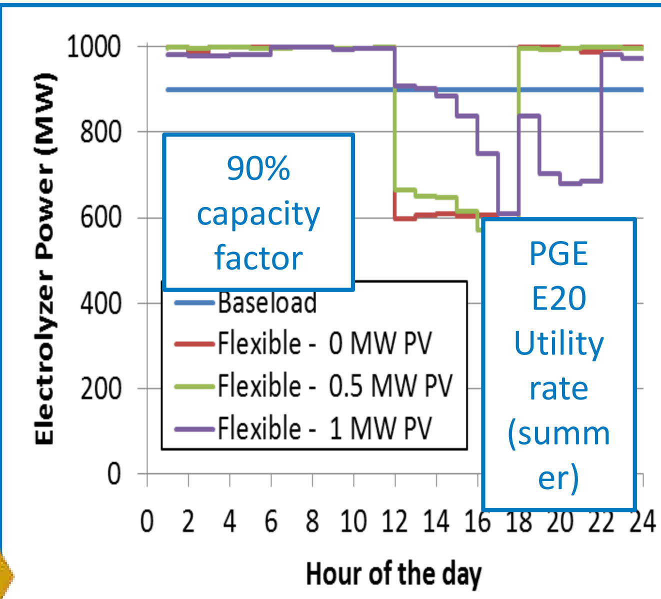
Device Optimization for grid integration using RODeO

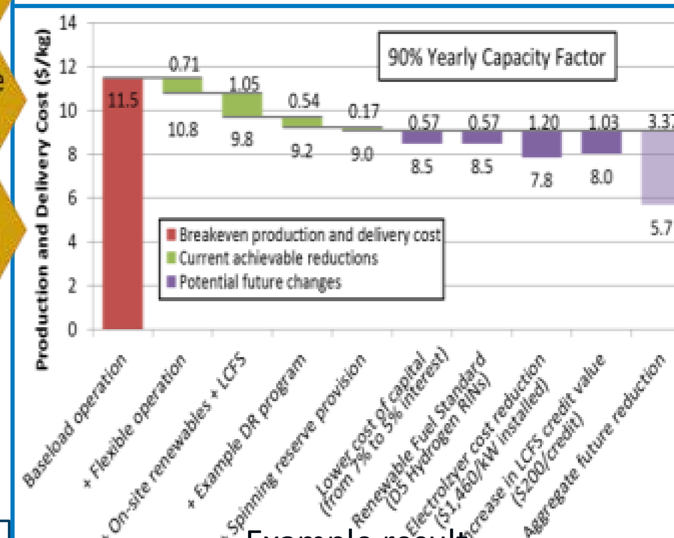
- RODeO (Revenue Operation and Device Optimization Model) optimizes uses mixed-integer linear programming to maximize revenue and optimize equipment operation

Includes:

- Retail and wholesale market integration
- Capital, FOM and VOM are included
- On-site generation (e.g., PV or Wind)
- Additional building load
- Ability to be used as a model predictive controller







Example result (www.nrel.gov/docs/fy17osti/67384.pdf)

RODeO optimizes device operation to understand economic competitiveness

Desired Outputs

- At a high level…
  - Market points that trigger the decisions made by the solar facility owner
  - Additional value created by the hydrogen system
  - Consider how a system would be sized for PG&E's PV solar station in Vacaville
  - Specify how the design would change in other high-solar regions of California
    (i.e., region, solar insolation, distances from hydrogen fuel demand, etc.)
- Specifics…
  - Optimal size of the electrolyzer
  - Optimal size of the hydrogen storage tank
  - Breakdown of optimal electrolyzer operation by service provided
  - Potential impact on excess solar generation
  - Impacts to electrolyzer performance caused by participation in ancillary services markets
- Are we missing anything?

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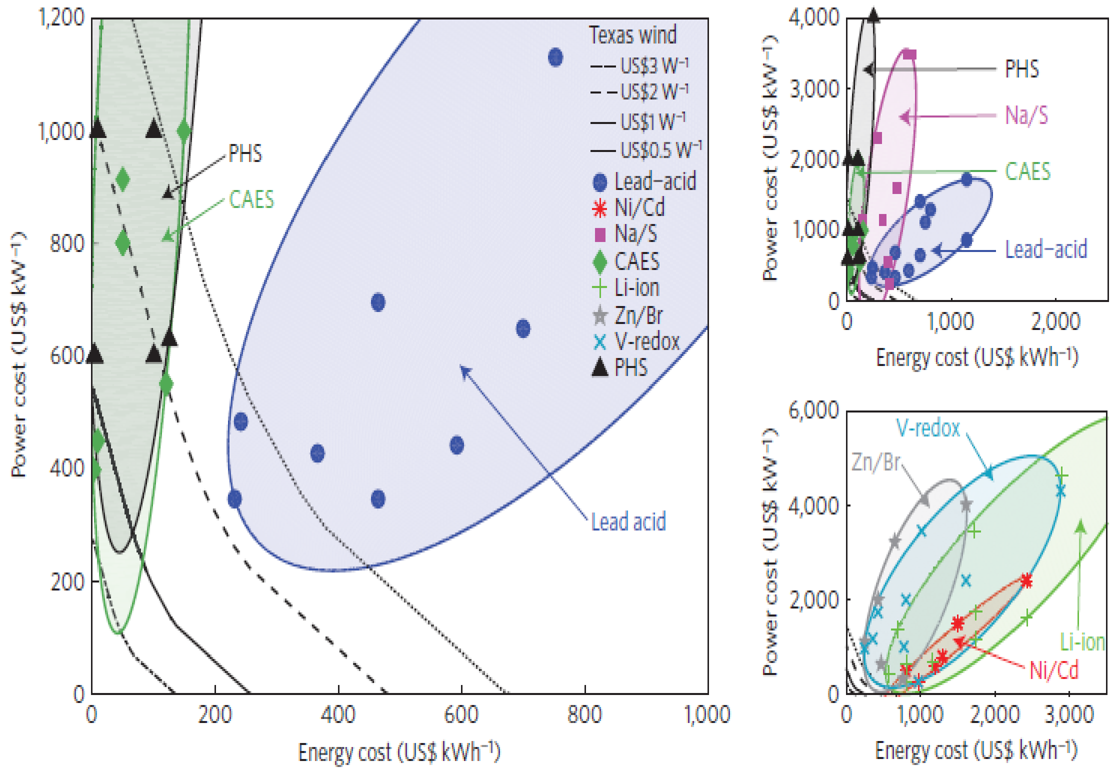
Energy storage benefit for renewables



Source: Braff et al., 2016. Value of storage technologies for wind and solar energy. Natur