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

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Outline

• NREL Team
• Goal and objectives
• Project Team and Roles
• Tasks and schedule
• Deliverables
• Previous studies
• 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

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
</tr>
</thead>
</table>
| 1.0  | Data collection  
| 1.   | Collect necessary location, cost and resource data  
| 1.   | Determine eligible credits and incentives  
| 2.0  | Perform optimization  
| 2.   | Prepare optimization model to integrate PV and electrolysis and setup desired scenarios  
| 2.   | Perform integrated solar-electrolysis optimization at |

Collect necessary cost, resource and location data  
Determine eligible credits and incentives  
Prepare optimization model and scenarios  
Perform optimization at candidate locations  
Characterize opportunity in other California regions  
Draft report to PG&E, DOE, and other stakeholders  
Publish final report  
Prepare Status Updates
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
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
• 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
For 1MW electrolyzer with truck delivery of hydrogen for FCEVs

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.

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

Summary

<table>
<thead>
<tr>
<th>Utility</th>
<th>Utility Rates</th>
<th>Ancillary Service Value</th>
<th>Average Energy Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCE</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>PG&amp;E</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>SDGE</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

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.

### Table: P2H Business Cases

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

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

Blue bars represent a range of potential prices at which hydrogen can be sold ($3-10/kg)
Assumed value of grid services and hydrogen, less feedstock costs received by FC, EY or SMR


### Technologies

<table>
<thead>
<tr>
<th>Name</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>HYPS</td>
<td>Pumped Hydro</td>
</tr>
<tr>
<td>Batt</td>
<td>Battery</td>
</tr>
<tr>
<td>FC</td>
<td>Fuel Cell</td>
</tr>
<tr>
<td>EY</td>
<td>Electrolyzer</td>
</tr>
<tr>
<td>SMR</td>
<td>Steam Methane Reformer</td>
</tr>
</tbody>
</table>

### Services

<table>
<thead>
<tr>
<th>Name</th>
<th>Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>All Ancillary Services</td>
</tr>
<tr>
<td>Eonly</td>
<td>Energy Arbitrage only</td>
</tr>
<tr>
<td>Baseload</td>
<td>“Flat” operation</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Return on Investment (year)</th>
<th>Total benefits in NPV (M€/yr)</th>
<th>Hydrogen price (€/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BENCHMARK</td>
<td>/</td>
<td>4.15</td>
</tr>
<tr>
<td>Scenario I</td>
<td>Inf</td>
<td>4.15</td>
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<tr>
<td></td>
<td></td>
<td>0</td>
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<tr>
<td>Scenario II</td>
<td>24.4</td>
<td>4.61</td>
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<tr>
<td></td>
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<td>2</td>
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<td>Scenario III</td>
<td>5.5</td>
<td>7.02</td>
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<tr>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Scenario IV</td>
<td>2.6</td>
<td>13.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
</tr>
</tbody>
</table>

Approach
Equipment Configuration (all systems have access to wholesale service)

- PV only
- PV + Electrolysis
- PV + Electrolysis + Fuel Cell

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

• Photovoltaic
  o Incentives and credits
  o Sale of electricity
  o Renewable credits

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

• Fuel Cell
  o Incentives and credits
  o Sale of electricity
  o Grid services (e.g., energy, capacity, ancillary services)
  o 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)
Desired Outputs

• At a high level...
  o Market points that trigger the decisions made by the solar facility owner
  o Additional value created by the hydrogen system
  o Consider how a system would be sized for PG&E’s PV solar station in Vacaville
  o 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...
  o Optimal size of the electrolyzer
  o Optimal size of the hydrogen storage tank
  o Breakdown of optimal electrolyzer operation by service provided
  o Potential impact on excess solar generation
  o Impacts to electrolyzer performance caused by participation in ancillary services markets

• Are we missing anything?
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Omar Guerra Fernandez: OmarJose.GuerraFernandez@nrel.gov
Energy storage benefit for renewables

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