Hybrid Hydrogen Energy Storage

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Talk Overview

Key Components of H$_2$ Storage

Case Study of Islanded Hybrid-H$_2$ Storage

Concept of Power to Gas Energy Storage
What is an Electrolyzer?

Electrolyzers can respond instantaneously to power fluctuations, thus offering high frequency dispatchability.

For every cubic foot of H₂ produced, half cubic foot of O₂ is produced.

H₂ and O₂ are produced at high purity.

H₂O + electricity \rightarrow H₂ + \frac{1}{2} O₂

Ideal energy = 39 kWh/kg H2, HHV
Electrolyzer Types

<table>
<thead>
<tr>
<th>Electrolyzer Type</th>
<th>Capacity (kW)</th>
<th>Efficiency HHV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkaline</td>
<td>1 – 2,300</td>
<td>72%</td>
</tr>
<tr>
<td>PEM</td>
<td>1 – 130</td>
<td>60%</td>
</tr>
<tr>
<td>Solid Oxide</td>
<td>pilot scale only</td>
<td>82%</td>
</tr>
</tbody>
</table>

- **Alkaline** technology is commercially available.
- **Proton Exchange Membrane (PEM)** systems are available in smaller capacities, but offer long term performance and cost benefits.
- **Solid Oxide Electrolyzers (SOEC)** are in development and will offer very high efficiency and low cost.

All electrolyzer costs are approximately $1000 per kW in MW-scale context.

References:
- **Alkaline**: NEL-Hydrogen system specifications
- **PEM**: Proton On-Site system specifications
- **Solid Oxide**: NREL/DOE internal systems analysis and cost estimations, 2011
Alkaline Electrolyzers – Largest Installations

Norsk Hydro’s 30,000 Nm³/h (~150 MW) Electrolyzer Plant (1948 - 1990)

Connected to a hydroelectric plant, generating about 70,000 kg/day

Reference: Knut Harg, Hydro Oil & Energy, Hydrogen Technologies
NAS – Hydrogen Resource Committee, April 19, 2007
# Hydrogen Storage Types

<table>
<thead>
<tr>
<th>Storage Type</th>
<th>$H_2$ Storage cost $$/kWh*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrestrial compressed tank**</td>
<td>$45</td>
</tr>
<tr>
<td>Deep-ocean gas storage***</td>
<td>$10</td>
</tr>
<tr>
<td>Liquid hydrogen storage**</td>
<td>$2.5</td>
</tr>
<tr>
<td>Geologic storage (porous rock formations)</td>
<td>$0.50</td>
</tr>
<tr>
<td>Dry-mined salt caverns</td>
<td>$0.25</td>
</tr>
<tr>
<td>Solution-mined salt caverns</td>
<td>$0.05</td>
</tr>
</tbody>
</table>

* using 20 kWh/kg $H_2$ (51% HHV efficiency)
** using H2A components model cost estimates
*** NREL cost estimate

Deep ocean gas storage: NREL internal cost estimation, 2010
# Power Generation Equipment

<table>
<thead>
<tr>
<th>Generator Type</th>
<th>Scale MW</th>
<th>Cost $/kW</th>
<th>Efficiency (HHV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combine cycle (CC) plant</td>
<td>50 - 550</td>
<td>$550-720</td>
<td>51%</td>
</tr>
<tr>
<td>Oxy-combustion CC</td>
<td>50 - 550</td>
<td>$550-720*</td>
<td>62%</td>
</tr>
<tr>
<td>PEM Fuel Cells</td>
<td>0.1 - 1.0</td>
<td>$2,500-5,000</td>
<td>40%</td>
</tr>
<tr>
<td>SOFC Fuel Cells</td>
<td>0.01 - TBD</td>
<td>$4,500</td>
<td>61%</td>
</tr>
</tbody>
</table>

Only PEM Fuel Cells have been demonstrated for H₂ to power for grid support.

* Oxy-combustion plant is assumed to have the same per-kW cost as CC. Oxy-combustion has many simplifying aspects over air-combustion CC.

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**References:**

**Combine Cycle:** “Cost and Performance Baseline for Fossil Energy Plants”, DOE/NETL, 2010
Attachment:


**Solid Oxide:** NREL/DOE internal systems analysis and cost estimations, 2011

**PEM Fuel Cells:** Personal communication with Kevin Bell from Ballard Power.
Talk Overview

Key Components of H₂ Storage

Case Study of Islanded Hybrid-H₂ Storage

Concept of Power to Gas Energy Storage
100% Hybrid Renewable Storage

- Renewable Electricity
- DC BUS
- Battery
- Electrolyzer
- Power Generator
- Inverter
- Demand
- Hydrogen Storage

Diurnal operation

Turns on when battery < ~70% state of charge
### 30,000 ft View of Storage Pros & Cons

<table>
<thead>
<tr>
<th>Energy storage system type</th>
<th>Round-trip efficiency</th>
<th>Bulk-energy storage cost (non-diurnal)</th>
<th>Ability to be refueled?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batteries only</td>
<td>80%</td>
<td>$700-$800/kWh</td>
<td>No</td>
</tr>
<tr>
<td>H₂ only</td>
<td>30%-50%</td>
<td>$0.05-$45/kWh</td>
<td>Yes</td>
</tr>
<tr>
<td>H₂ &amp; batteries (hybrid)</td>
<td>40%-70%</td>
<td>$0.05-$45/kWh</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Note: hybrid energy storage offers spill over capability for displacing transportation emissions via fuel cell vehicles.
Example Island Installation (Wind & Solar Resource)
Demand Mismatch (measured data)

Note: Solar power was used as well. It was relatively constant throughout the year.
Optimization Methodology

Gradient descent minimization of levelized cost of electricity (LCOE)

Optimization parameters (using HOMER model):

1. Size of solar panels - $5,500 /kW, no tracking
2. Number of wind turbines - $4,400 /kW, 1.8 MW each
3. Number of batteries - $745 / kWh, Xtreme Power DPR 1500
4. Capacity of power electronics - $609 /kW, rectifier & inverter
5. Size of fuel cell - $4,000 /kW, 40% HHV efficiency PEM
6. Size of electrolyzer - $1,000 /kW, 70% HHV efficiency Alkaline
7. Size of hydrogen storage - $700/kg, Terrestrial, steel tank

Note: only “off-the-shelf” technologies were used for this analysis.

Reference: Xtreme Power Battery: system specifications from Xtreme Power

concept illustration of gradient descent from wikipedia
Energy Storage State of Charge

Cumulative Energy to Load (MWH/year)
- Solar
- Wind
- Battery
- Fuel Cell
Energy Storage State of Charge

Stored energy in batteries (MWh)

Total batteries = 9 MWh, $6.8 million

Stored hydrogen (MWh)

Total H₂ stored = 150,000 kg, $105 million
100% renewable fraction solutions resulting LCOE:
- 100% hydrogen = 0.51 $/kWh
- Hybrid hydrogen = 0.43 $/kWh
- 100% batteries = 3.56 $/kWh
Best-in-class: SOEC, Salt Cavern, Oxy-Combustion

Plant components
- High – pressure electrolyzer (SOEC)
- Gas storage: solution mined salt dome
- $\text{H}_2/\text{O}_2$ turbine

Salt formation

- Hydrogen Solution Mine
- Oxygen Solution Mine

Distance: ~1km
## Hydrogen Production Technology

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<th>Power Gen. Technology</th>
<th>Component HHV efficiency</th>
<th>Alkaline</th>
<th>PEM</th>
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<tr>
<td>Air-combustion CC</td>
<td>51%</td>
<td>37%</td>
<td>31%</td>
<td>42%</td>
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<tr>
<td>Oxy-combustion CC</td>
<td>62%</td>
<td>45%</td>
<td>37%</td>
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<tr>
<td>SOFC</td>
<td>61%</td>
<td>44%</td>
<td>37%</td>
<td>50%</td>
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### Best in class for this location long-term:
- Solid oxide electrolyzer (SOEC) $1,000/kW (not available)
- Salt cavern storage $0.08/kWh (not available today)*
- Oxy-combustion CC $720/kW (not available today)

- **Levelized cost of electricity** = 20.2 ¢/kWh
  
  Note: ancillary service revenues can rival power production revenue

* Additional storage cost of $O_2$ increases cost from $.05 kWh to $.08 per kWh.
SOEC, Salt Cavern, Oxy-Combustion

NPV of Equipment Cost (including O&M)

- Solar panels
- Wind turbines
- H₂/O₂ turbine
- Batteries
- Power electronics
- Electrolyzer
- Hydrogen storage

Net present value (millions of $)
Key Technologies

Oxy-combustion hydrogen turbines
- Enables low-cost, high-round trip energy storage
- Engineering development required
- No scientific breakthroughs needed

Solid oxide electrolyzers, high-pressure
- Enables low-cost, high-round trip energy storage
- Solid oxide materials are ideal for high-pressure operation
  (low back-diffusion due to material impermeability)
- Science & engineering development required
- 1000’s of hours of operation have been demonstrated on modules
- High pressure operation has been demonstrated on stacks
Talk Overview

Key Components of H₂ Storage

Case Study of Islanded Hybrid-H₂ Storage

Concept of Power to Gas Energy Storage
Natural gas pipelines can operate with 10% H₂ (as much as 20% has been commercially demonstrated).
Questions?
BACKUP SLIDES
Hydrogen Storage (Terrestrial)

300 kg H2 storage in ISO containers, in Pearl Harbor Hickham
Power Generation (Fuel Cell)

1.1 MW Ballard Hydrogen Fuel Cell @ Toyota Headquarters in CA
Toshiba Advanced H$_2$/O$_2$ Cycle

This cycle is a hybrid between a combustion and steam turbine. Toshiba predicts 61.7% HHV or 72.8% LHV efficiency for this cycle.
Siemens installation of oxygen-blown combustion turbine.
They experience efficiency gain of 10% on LHV basis over conventional systems.
This system is developed for CO2 sequestration.
Ongoing Efforts in $O_2$ Turbines

![Diagram of Oxy-steam cycle rig/demonstrator](image)

**Figure 10: Modified J79 Combustion System for Oxy-steam Cycle Rig/Demonstrator**
Combine Cycle (CC) Turbine

Combine cycle plants are commonly designed for peaking power. Their fuel is more expensive than base-load coal plants. Plant efficiency 55-58% LHV.
CC Major Differences With H₂/O₂

- **Pre-cooler & compressor not present with H₂/O₂**
  - No NOₓ formation.
  - Need steam recycle

- **Exhaust NOₓ clean-up would be obsolete. Exhaust would be liquid H₂O**

- **Bottoming Steam Cycle is Integrated**
Alkaline Electrolyzers

NEL-Hydrogen Electrolyzers – 2.3 MW per unit

http://www.nel-hydrogen.com/
Proton Exchange Membrane (PEM) Electrolyzers

60 kg/day electrolyzer from Proton OnSite:

http://www.protononsite.com/
Solid Oxide Electrolyzers (SOEC)

- **Electricity, DC**
- **Steam**
- **650°C**
- **Hydrogen**
- **800°C**
- **Oxygen**

SOEC has very high efficiency due to thermal weakening of H-O bonds.

http://www.versa-power.com/
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Best in class for this location long-term:

- Solid oxide electrolyzer (SOEC) $1,000/kW (not available)
- Deep water storage, $15/kWh (not available today)*
- Oxy-combustion CC $720/kW (not available today)

- LCOE hybrid = 32¢/kWh

* Additional storage cost of O2 increases cost from $10 kWh to $15 per kWh.
SOEC, Deep Water Storage, Oxy-Combustion

NPV of Equipment Cost

Cash Flow Summary
## Alkaline, Salt Cavern, Oxy-Combustion

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**Best in class for this location long-term:**
- Alkaline electrolyzer: $1,000/kW
- Salt cavern storage: $0.08/kWh (not available today)*
- Oxy-combustion CC: $720/kW (not available today)

- LCOE hybrid = 21.3 ¢/kWh
Alkaline, Salt Cavern, Oxy-Combustion

NPV of Equipment Cost

Cash Flow Summary