NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Scenario Development and Analysis of Hydrogen as a Large-Scale Energy Storage Medium

RMEL Meeting

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Introduction

NREL Project Team

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Is Hydrogen a Viable Energy Storage Medium?

Objective:

Evaluate the economic viability of the use of hydrogen for medium- to large-scale energy storage applications in comparison with other electricity storage technologies

Strategy:

Develop potentially viable hydrogen production and storage scenarios

Perform a lifecycle economic analysis to determine the levelized cost of delivering energy for the hydrogen scenarios

Benchmark against competing technologies on an "apples to apples" basis

- Batteries
- Pumped hydro
- Compressed Air Energy Storage

Benchmarking Study: "Apples to Apples" Analysis

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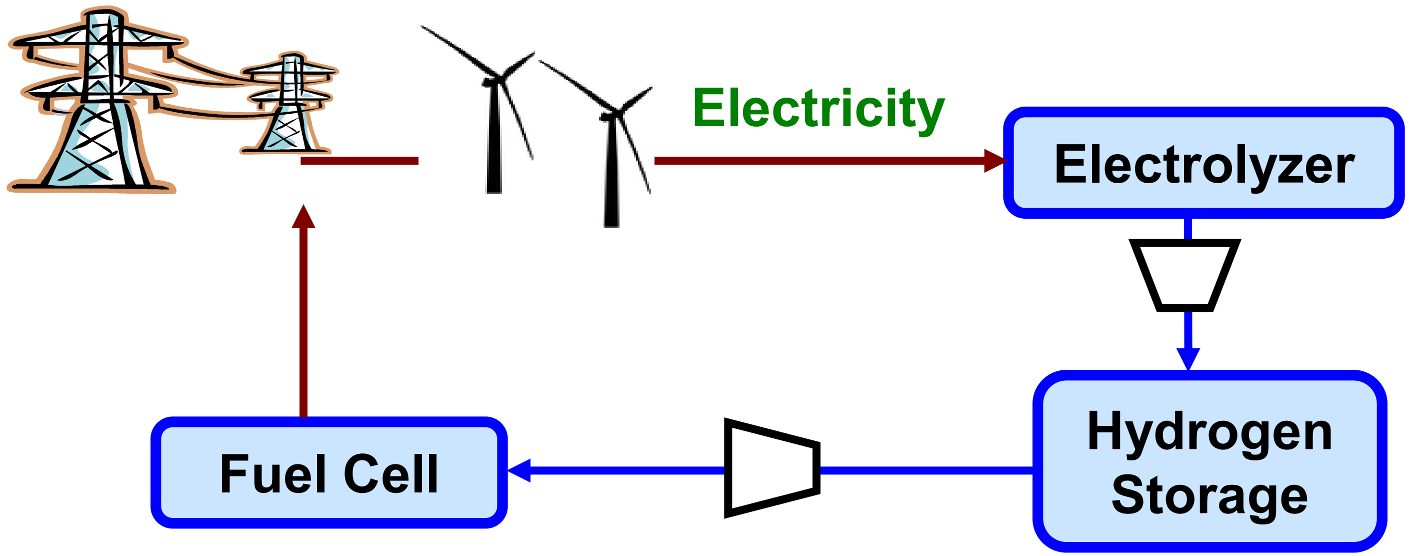
Hydrogen for Bulk Energy Storage—Simple Scenario

Energy Arbitrage—Grid/renewable electricity is electrolyzed to produce hydrogen when demand is low and/or renewables must be purchased. Hydrogen is stored for use in a dispatchable fuel cell to provide power during periods of peak demand.

- Primary figure of merit is levelized cost of delivered electricity
- Storage system may also meet requirements for spinning reserve and other services, but no value is assigned to these services



Study Framework—System Configuration

- 50MW for 6 peak hours each weekday (300 MWh/day)
- Two basic storage system configurations, both using an electrolyzer system to produce hydrogen and a fuel cell system to produce electricity:
  - Case 1: Steel tank storage (above ground)
  - Case 2: Geologic storage
- 3 timeframes/cost values considered:
  - Near-term: Up to 2010 (current or high cost)
  - Mid-term: 2010–2020
  - Long-term: 2020–2030 (future assumed low cost)
- Long-term case meant to represent best-case scenario for hydrogen-based energy storage using stretch goals based on fully mature, optimized hydrogen technologies

Study Framework—Facility Life Economic Analysis

Financial Assumptions

- 40-year plant life (Some equipment will be replaced at more frequent intervals.)
- 10% after-tax internal rate of return
- 100% equity financing

Cost Assumptions

- Electricity is purchased from the grid during off-peak hours at 3.8¢/kWh (lower-bound cost) or 6¢/kWh (upper-bound case)
- Natural gas is purchased at $5/mmBtu for the CAES system

Study Framework— Facility Life Economic Analysis

Facility Lifecycle Economic Analysis Using the HOMER Model

- NREL distributed generation economic model (https://analysis.nrel.gov/homer)
- Least cost system optimization based on subsystem component costs and resource and load characteristics
- Model output is levelized cost (¢/kWh) of output electricity from the system

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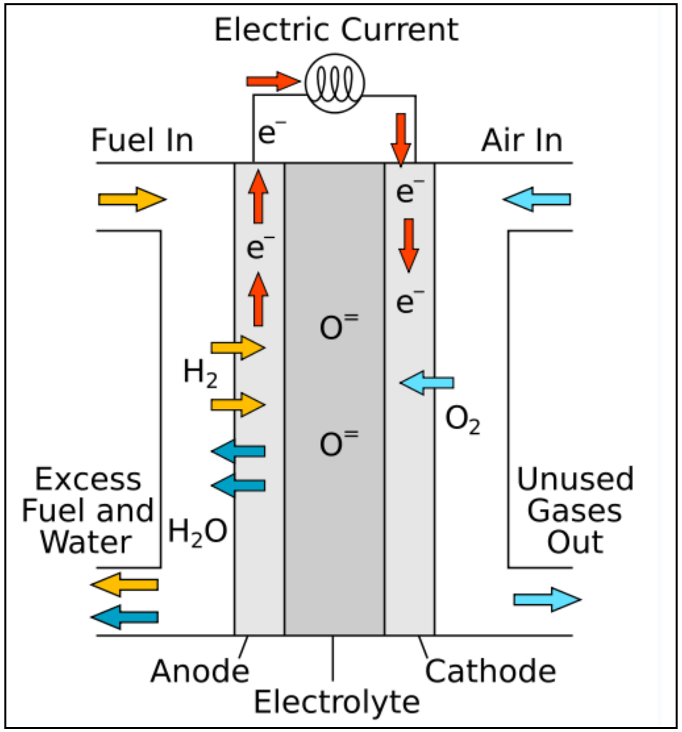
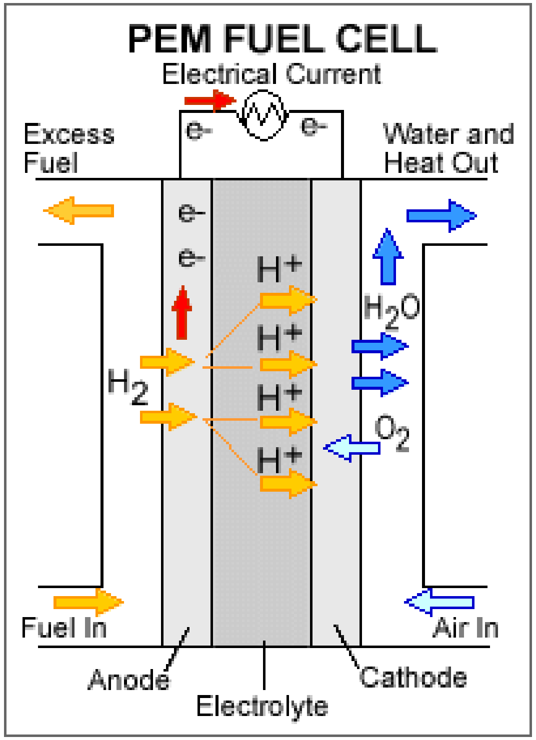
Fuel Cell Subsystem

Solid Oxide Fuel Cell (SOFC)



Polymer Electrolyte Fuel Cell (PEM) (a.k.a., Proton Exchange Membrane Fuel Cell)



Sources: http://en.wikipedia.org/wiki/Proton_exchange_membrane_fuel_cell
http://en.wikipedia.org/wiki/Solid_oxide_fuel_cell

Fuel Cell Subsystem

SOFC—Solid Oxide Fuel Cell
PEM—Polymer Electrolyte Membrane Fuel Cell

	Current Timeframe Value		Future Timeframe Value	
System component	SOFC	PEM	SOFC	PEM
Fuel Cell System installed capital cost	$900/kW	$3,000/kW	$390/kW	$400/kW
Stack replacement frequency/cost	10 years/30% of initial capital cost	13 years /30% of initial capital cost	10 years/30% of initial capital cost	26 years /30% of initial capital cost
O&M costs	$27/kW-yr.	$50/kW-yr.	$12/kW-yr.	$20/kW-yr.
Fuel cell life	10 yr. (15,660 h operation)	13 yr. (20,000 h operation)	10 yr. (15,660 h operation)	26 yr. (40,000 h operation)
Fuel cell system efficiency	60%	42%	70%	53%
Power converter efficiency	N/A	90%	N/A	90%

Electrolyzer and Storage Subsystems

	Current Timeframe Value	Future Timeframe Value
Electrolyzer		
System Efficiency	73% (HHV)	87% (HHV)
Capital Cost	$675/kW	$300/kW
Steel Tank Storage		
Capital Cost (28,600 kg nominal storage example*, Hydrogen compressed to 2500 psi)	$30.7M (includes compressor)	$12.3M (includes compressor)
Geologic Storage		
Capital Cost (28,600 kg nominal storage, Hydrogen compressed to 1800 psi)	$7.8M (includes compressor)	$5.8M (includes compressor)

***Storage costs shown are for 28,600 kg example. Modeled storage volume and costs are determined for each case and timeframe.**

Cost of Energy for PEM Fuel Cell vs. Solid Oxide Fuel Cell

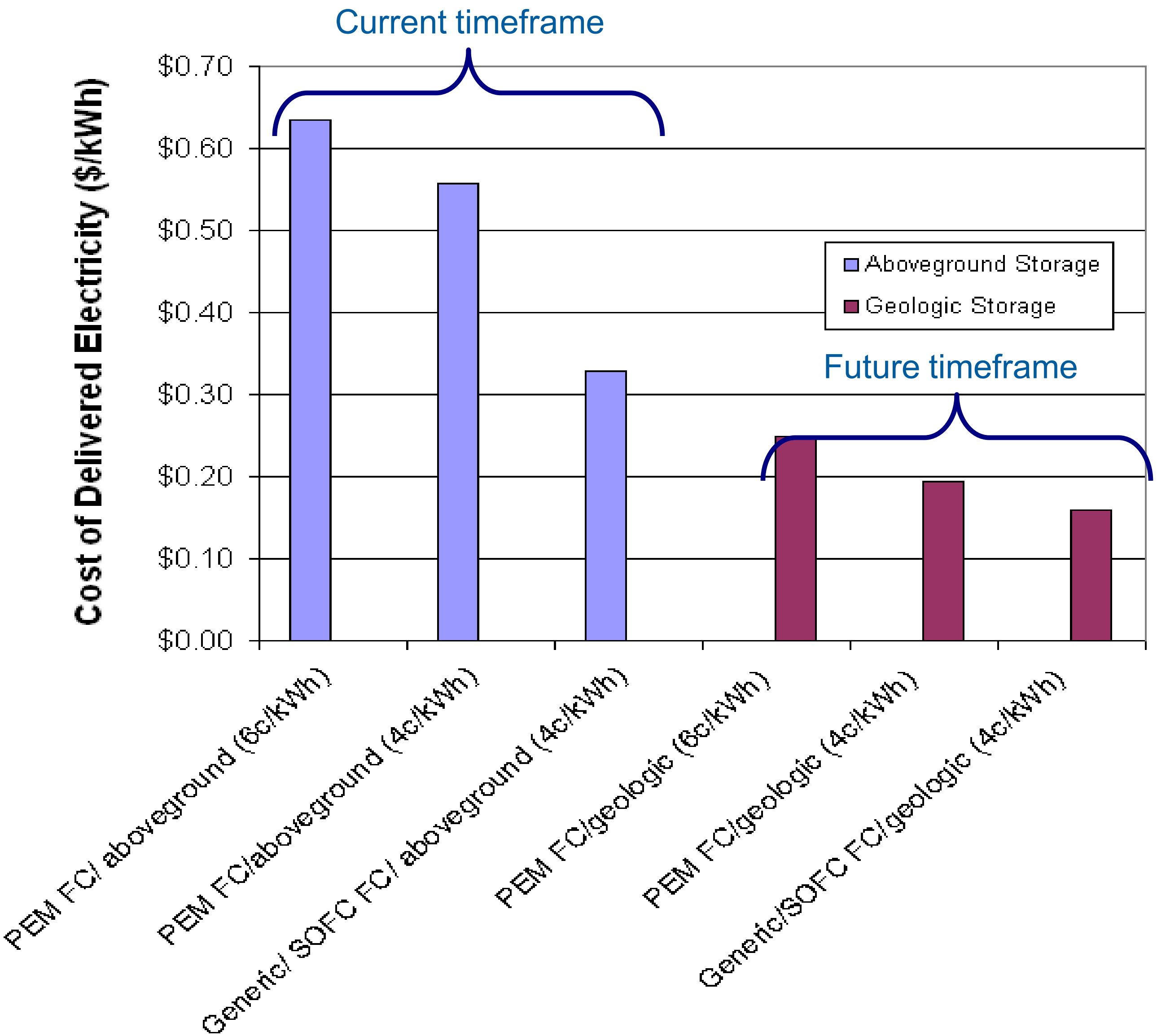


Chart represents "bounding case" information

-High Cost Bounding Case: **Current timeframe, aboveground storage**

- Low Cost Bounding Case: **Future timeframe, geologic storage**

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Benchmarking Analysis—Evaluate all Technologies for the Same Scenario

- Analysis of competing technologies within the same study framework as the original analysis and bounding cases
  - **Current timeframe**—High cost due to technology immaturity and few installations
    - Actual installations and costs when available
  - **Future timeframe**—Lower cost due to technology maturity and more installations
    - Best available information on projected costs and DOE targets
- Competing Technologies
  - Batteries
    - Nickel Cadmium
    - Sodium Sulfur
    - Vanadium Redox
  - Pumped Hydro
  - Compressed Air Energy Storage

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Benchmarking Analysis—Batteries

Three Battery Technologies

Nickel Cadmium

- Demonstrated utility-scale project outside Fairbanks Alaska: 13 MWh (26 MW at 30 min.)

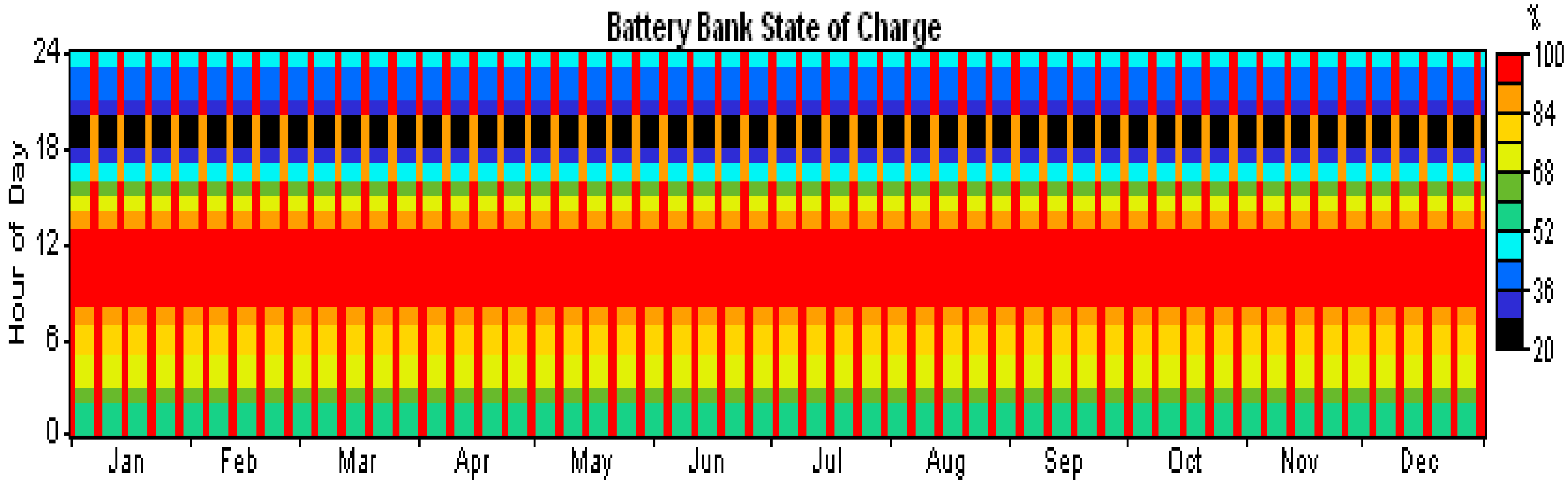
Sodium Sulfur

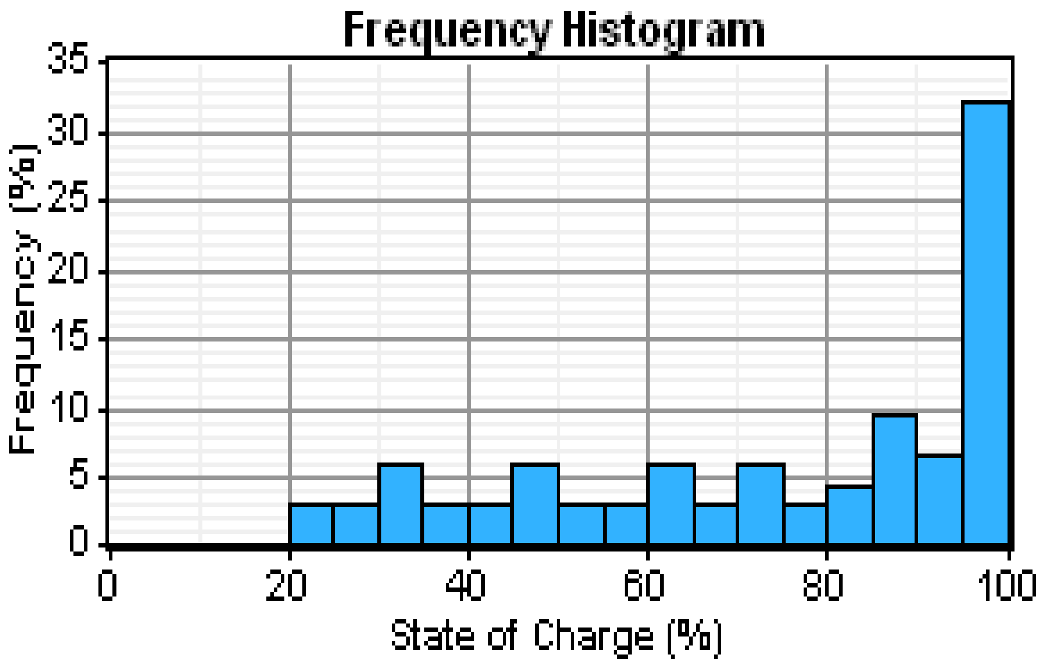
- NGK Insulators Ltd. of Japan is currently the only supplier.
- Tokyo Electric Power Company (TEPCO) has developed several utility-scale projects with NGK. Demonstration projects range from 500 kW to 6 MW in scale including two 48-MWh plants.

Vanadium Redox Flow Batteries

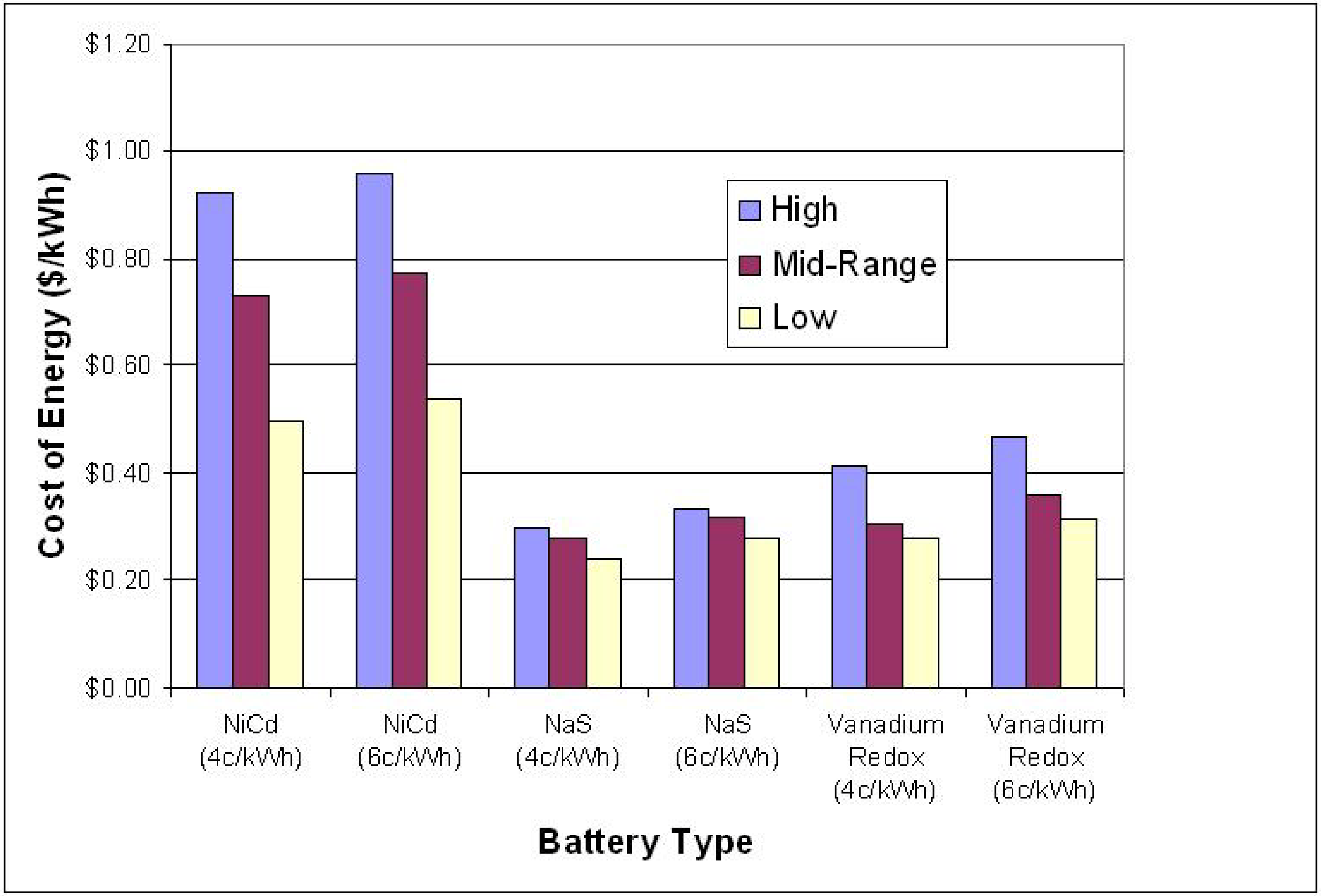
- Currently, the major suppliers of Vanadium Redox batteries are VRB Power Systems, Inc. of Canada and Sumitomo Electric Industries (SEI) of Japan.
- Demonstrated installations range in size from 3 MW for 1.5 seconds of storage to 500 kW for up to 10 hours of storage.

Battery Charge Characteristics—NiCd Example





Battery System Cost of Output Energy



The cost of NiCd batteries is high in comparison to sodium sulfur and Vanadium Redox batteries due to relatively high capacity ($/kWh) costs.

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Benchmarking Analysis—Pumped Hydro and CAES

Pumped Hydro

The first plant built in the United States in 1928–29 featured two 3-MW reversible turbines.

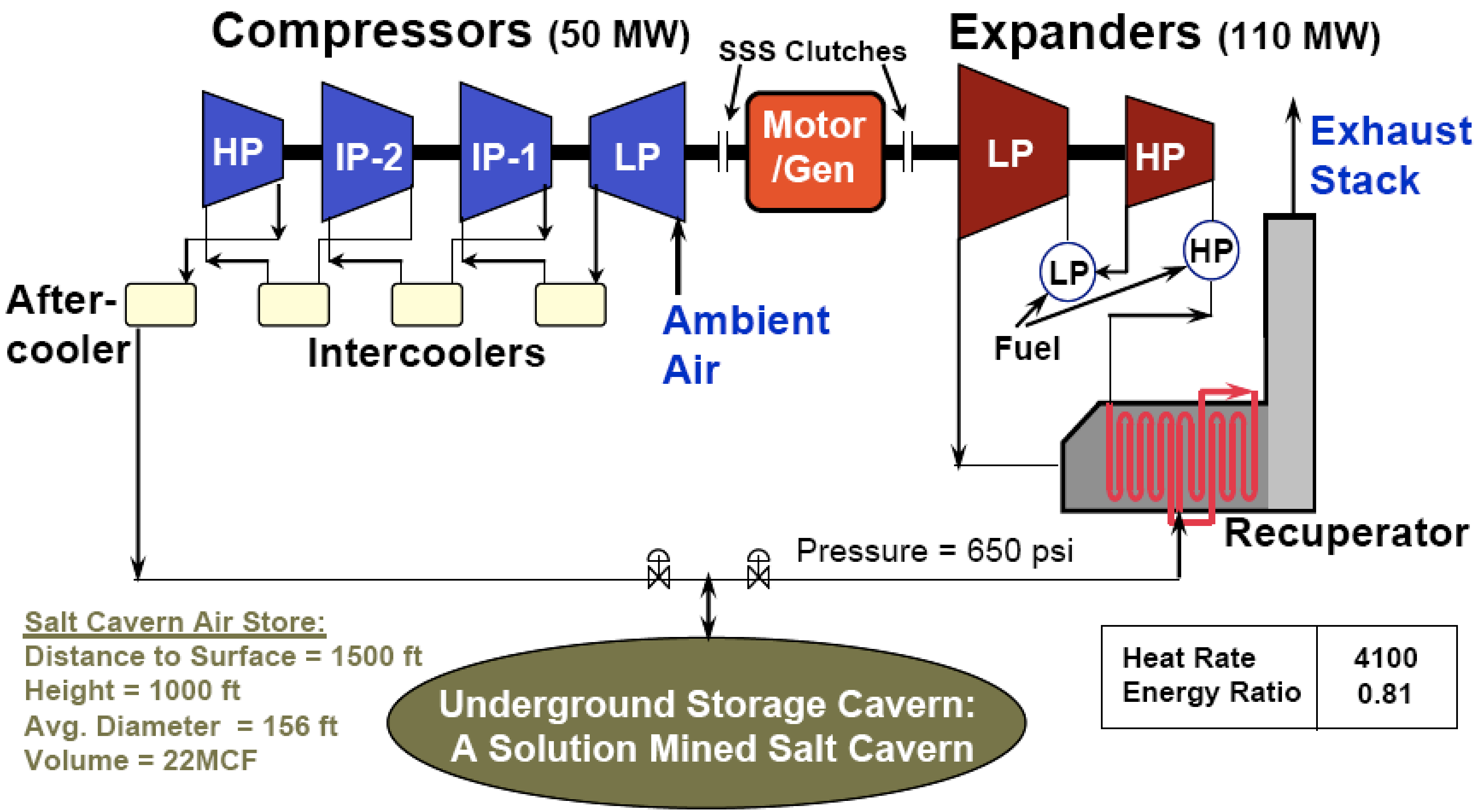
Today, pumped hydro capacity in the United States is about 19,000 MW.

Compressed Air Energy Storage

There are two major CAES installations in Huntorf, Germany (built in the 1970s) and in McIntosh, Alabama (built in the 1990s).

Plants, built and proposed, range in size from 110 MW to 2700 MW.

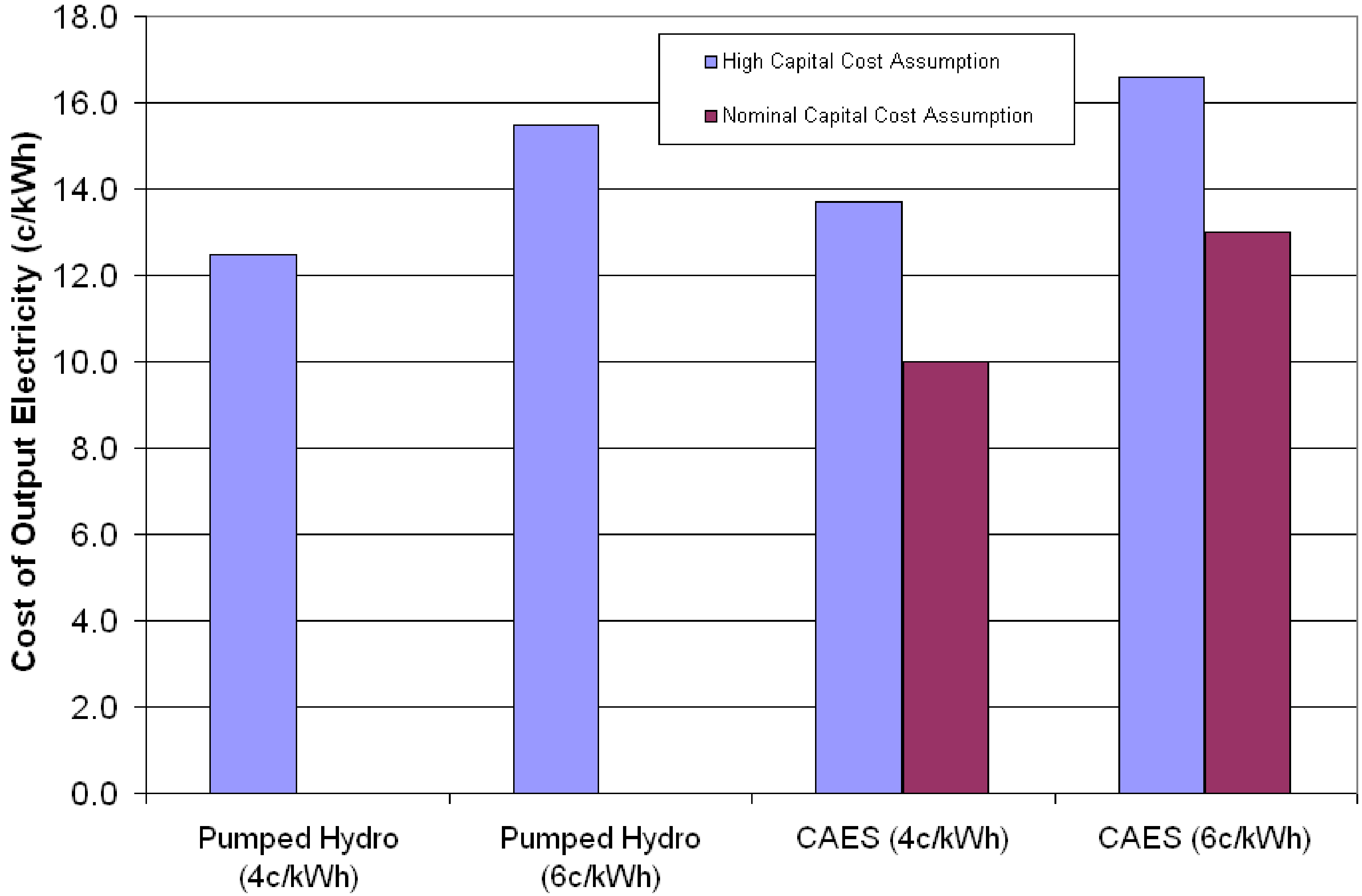
Schematic for Alabama McIntosh 110-MW CAES Plant



Source: Nakhamkin, M., and M. Chiruvolu, *Available Compressed Air Energy Storage (CAES) Concepts.*

Benchmarking Analysis—Pumped Hydro and CAES

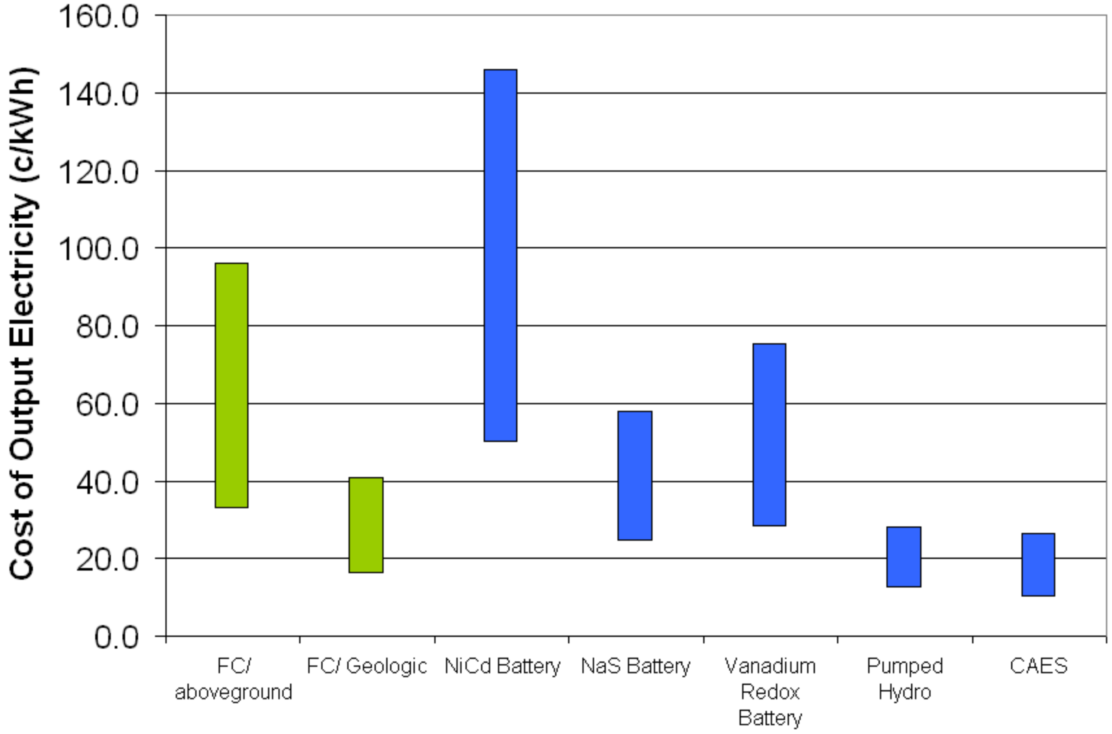
Both technologies are low cost relative to hydrogen fuel cells or batteries.



Benchmarking Cost Analysis Results

Hydrogen could be competitive with alternative technologies for the bulk electricity storage (50 MW, 6 hours) scenario analyzed.

- As fuel cell technology matures, electricity could be produced from geologically stored hydrogen for under 20¢/kWh.
- Because of its high energy density, aboveground storage of hydrogen could be competitive in locations where CAES and pumped hydro are not feasible.



Benchmarking—Other Benefits and Drawbacks of Hydrogen Energy Storage Relative to Alternatives

System Operation	
Benefits	**Drawbacks**
Modular (can size the electrolyzer separately from FC to produce extra hydrogen)	Low electrolysis/FC round trip (AC to AC) efficiency (50–55%) Even lower round-trip efficiency when hydrogen is used in a combustion turbine (<40%)
Very high energy density for compressed hydrogen (>100 times the energy density for compressed air at 120 bar ΔP, CC GT)	Hydrogen storage in geologic formations other than salt caverns may not be feasible
System can be fully discharged at all current levels	Electrolyzers and fuel cells require cooling
Cost	
Benefits	**Drawbacks**
Research has potential to drive down costs	Use of precious metal catalysts for low-temperature fuel cells
	Currently high cost relative to competing technologies (>$1,000/kW)

Source: Crotogino and Huebner, *Energy Storage in Salt Caverns / Developments and Concrete Projects for Adiabatic Compressed Air and for Hydrogen Storage,* SMRI Spring 2008 Technical Conference, Portugal, April 2008.

Benefits and Drawbacks of Hydrogen Energy Storage

Environmental	
Benefits	**Drawbacks**
Catalyst can be reclaimed at end of life	Environmental impacts of mining and manufacturing of catalyst
	Low round-trip efficiency increases emissions for conventional electricity and reduces replacement by renewables

Source: Denholm, Paul, and Gerald L. Kulcinski, *Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems,* Energy Conversion and Management, 45 (2004) 2153-2172.

Benefits and Drawbacks of Battery Energy Storage

System Operation	
Benefits	**Drawbacks**
Modular	Battery voltage to current relationship limits the amount of energy that can be extracted, especially at high current
Mid range to high round trip efficiency (65–75%)	
Cost	
Benefits	**Drawbacks**
Sodium sulfur and Vanadium Redox battery system cost	Nickel cadmium battery system cost
High round-trip efficiency reduces arbitrage scenario costs	
Environmental	
Benefits	**Drawbacks**
	Toxic and hazardous materials

Source: EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, 2003, EPRI, Palo Alto, CA and the U.S. Department of Energy, Washington, DC.

Benefits and Drawbacks of Pumped Hydro Energy Storage

System Operation	
Benefits	**Drawbacks**
Well established and simple technology	System requires large reservoir of water (or suitable location for reservoir)
High round-trip efficiency (70–80%)	System requires mountainous terrain
	Extremely low energy density (0.7 kWh/m^3)
Cost	
Benefits	**Drawbacks**
Inexpensive to build and operate	
Environmental	
Benefits	**Drawbacks**
No toxic or hazardous materials	Large water losses due to evaporation, especially in dry climates
	Habitat loss due to reservoir flooding
	Stream flow and fish migration disruption

Source: Denholm, Paul, and Gerald L. Kulcinski, *Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems,* Energy Conversion and Management, 45 (2004) 2153-2172.

Benefits and Drawbacks of Compressed Air Energy Storage

System Operation	
Benefits	**Drawbacks**
Proposed advanced designs store heat from compression giving theoretical efficiency of 70%—comparable to pumped hydro	Low round-trip efficiency (54%) with waste heat from combustion used to heat expanding air—42% without
	Very low storage energy density (2.4 kWh/m^3)
	Must be located near suitable geologic caverns
Cost	
Benefits	**Drawbacks**
Low cost	
Environmental	
Benefits	**Drawbacks**
	Approximately 1/3 of output energy is derived from natural gas feed to combustion turbines resulting in additional GHG emissions

Source: Crotogino and Huebner, *Energy Storage in Salt Caverns / Developments and Concrete Projects for Adiabatic Compressed Air and for Hydrogen Storage,* SMRI Spring 2008 Technical Conference, Portugal, April 2008.

Conclusions

Hydrogen has several important advantages over competing technologies, including:

- Very high storage energy density (170 kWh/m^3 vs. 2.4 for CAES and 0.7 for pumped hydro)
  - Allows for potential economic viability of above-ground storage
- Relatively low environmental impact in comparison with other technologies

The major disadvantage of hydrogen energy storage is cost.

- Research and deployment of electrolyzers and fuel cells may reduce cost significantly.

Thank You

Questions?