<u>Electrical Energy Storage (EES)</u>

High Energy Applications & Technology

<u>Advanced Flow Battery Systems</u>

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ARPA-E "*GRIDS*" Project
Transformative Electrochemical Flow Storage System

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Outline

- Electrical Energy Storage (EES) has large, and growing, market potential
  - Conventional batteries are ideal for short-to-moderate Energy/Power ratios (*e.g.*, ≤ 1-h of discharge time at rated power output)
  - Many large-scale EES applications require higher E/P ratios
  - Flow-Cell technologies are well suited for these applications

- Key benefits of Flow-Cell technologies for EES can include:
  - Both High Energy and High Power
  - Good round-trip energy efficiencies
  - Long cycle life
  - High utilization of active materials
  - Minimize non-active materials

- Technology is proven, but not (yet) cost effective
  - Potential for future improvements is large
    - Minimal development effort to date (*e.g.*, relative to fuel cells)
  - Fuel-cell technology is very applicable here
    - Multiple types of Flow-Cell Systems possible

Electrical Energy Storage (EES)

Need is growing with increased Renewables, improved efficiency, Smart Grid, etc.

EES creates value in the entire electricity value chain

Electricity generation
- Conventional
- Renewable

↓

Electricity transmission and distribution (T&D)

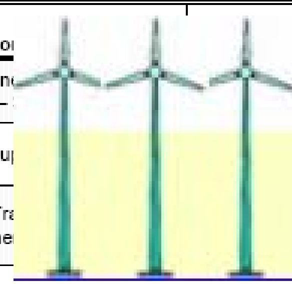
↓

Electricity consumption
- Residential
- Commercial
- Industrial

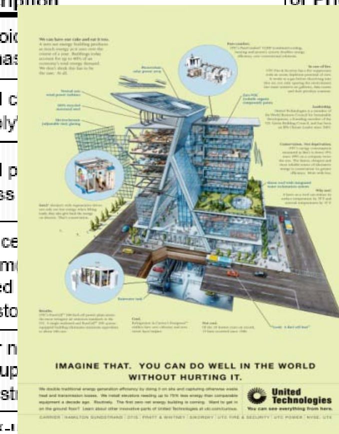
Table from "Guide to estimating benefits and market potential for electricity storage in New York (w/ emphasis on NYC)," NYSERDA Final Report 07-06, Mar 2007.

Table ES.1. Storage Applications and Benefits Summary Descriptions

#	Applicatio		Description	Cost Element(s) or Price Signal(s)
1	Electric En Buy Low –	OC - Efficiency)	1. Avoi purchas	DAM
2	Electric Su	acity (ICAP)	Avoid c "supply	ICAP ction
3	Reduce Tra Requireme	nsmission ges (TSCs)[2]	Avoid p access	Transmission Charge (TSCs)
4	Red Con		Reduce ystem elated ith sto	DAM (Congestion nent)
5	Transmission and Distribution Upgrade Deferral	Avoided Annual Revenue Requirement for T&D Upgrade	Defer n T&D up downst	revenue ment for upgrade.
6	Operat	lue	"Back-	ices (LBMP and city)
7	Regula Respo	lue		
8	Transm	n	Short duration support for transmission stability and improved throughput.	n/a
9	Electri	ted	Financial losses avoided due to improved PQ.	Value-of-Service as proxy
10	Ele		Financial losses avoided due to	-Service as proxy
11	Ele Demand Charges	Bill[2]		SC No. 9, Service Rate I
12	Electric Service Bill Reduction: Time-of-use Energy Prices	Reduced Electric S Bill[2]		SC No. 9, Service Rates II & III + Supply Charges
13	Renewable Electricity Production Time-shift	Enhanced Wind En Value		MP and "firmed " (ICAP) Credit.
14	Renewables Capacity Firming	Enhanced Pho Capacity Valu		and "firmed AP) Credit.



Renewable Energy
Smoothing & time-shifting



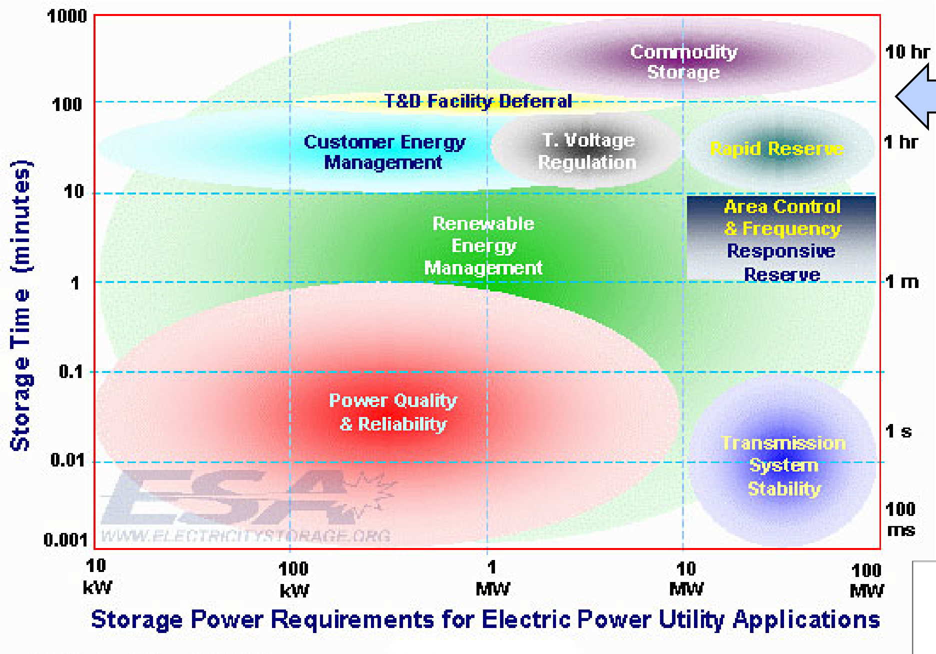
Commercial Buildings
Bill reduction & UPS

Remote & Off Grid
Minimize fuel usage

Transmission & Distribution
Infrastructure deferral

EES applications have wide range of requirements

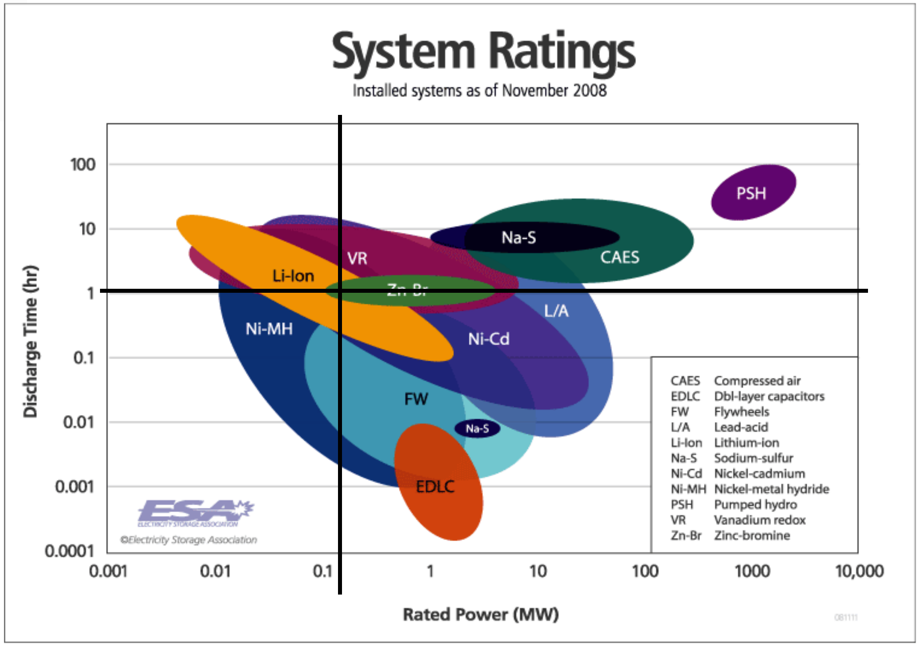
Large potential market (> $1B/y); EES is more efficient than alternatives



Data from Sandia Report 2002-1314

- Many potential **applications** for EES
- Provides means to balance fluctuating consumption & generation, as well as meet maximum power capacity requirements
- To store 1% of daily U.S. consumption requires 100 GWh/day (= $20B at $200/kWh installed cost)
- Largest EES markets are for applications that require E/P > 1-h and P > 100-kW

- Not many multi-hour EES **technologies**
- CAES and PSH are *not* readily deployable
- Difficult to deliver *both* high Power and high Energy with conventional batteries
- Conventional batteries (*e.g.*, Li-ion, Ni-MH, Ni-Cd, L/A) ideally suited for E/P ≤ 1-h apps



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EES Market Potential

Sandia report provides some estimates of multiple EES applications

	Type of EES Application	Discharge Duration (h)		Capacity (Power: kW, MW)		Benefit ($/kW)*		Potential (MW, 10 Years)		Economy ($Million)†		% of U.S.
#	Description	Low	High	Low	High	Low	High	CA	U.S.	CA	U.S.	Market
11	Time-of-Use Energy Cost Management	4	6	1 kW	1 MW	1,226	1,226	5,038	64,228	$6,177	$78,743	34.5%
12	Demand Charge Management	5	11	50 kW	10 MW	582	582	2,519	32,111	$1,466	$18,695	8.2%
15	Renewables Energy Time-Shift	3	5	1 kW	500 MW	233	389	2,889	36,834	$899	$11,455	5.0%
2	Electric Supply Capacity	4	6	1 MW	500 MW	359	710	1,445	18,417	$772	$9,838	4.3%
8	Transmission Congestion Relief	3	6	1 MW	100 MW	31	141	2,889	36,834	$248	$3,168	1.4%
9.1	T&D Upgrade Deferral 50th percentile	3	6	250 kW	5 MW	481	687	386	4,986	$226	$2,912	1.3%
9.2	T&D Upgrade Deferral 90th percentile††	3	6	250 kW	2 MW	759	1,079	77	997	$71	$916	0.4%
10	Substation Onsite Power	8	16	1.5 kW	5 kW	1,800	3,000	20	250	$47	$600	0.3%
16	Renewables Capacity Firming	2	4	1 kW	500 MW	709	915	2,889	36,834	$2,346	$29,909	13.1%
3	Load Following	2	4	1 MW	500 MW	600	1,000	2,889	36,834	$2,312	$29,467	12.9%
1	Electric Energy Time-shift	2	8	1 MW	500 MW	400	700	1,445	18,417	$795	$10,129	4.4%
17	Wind Generation Grid Integration, Long Duration	1	6	0.2 kW	500 MW	100	782	1,445	18,417	$637	$8,122	3.6%
5	Electric Supply Reserve Capacity	1	2	1 MW	500 MW	57	225	636	5,986	$90	$844	0.4%
13	Electric Service Reliability	0.0833	1	0.2 kW	10 MW	359	978	722	9,209	$483	$6,154	2.7%
14	Electric Service Power Quality	0.0028	0.0167	0.2 kW	10 MW	359	978	722	9,209	$483	$6,154	2.7%
6	Voltage Support	0.25	1	1 MW	10 MW	400	400	722	9,209	$433	$5,525	2.4%
7	Transmission Support	0.0006	0.0014	10 MW	100 MW	192	192	1,084	13,813	$208	$2,646	1.2%
17	Wind Generation Grid Integration, Short Duration	0.0028	0.25	0.2 kW	500 MW	500	1,000	181	2,302	$135	$1,727	0.8%
4	Area Regulation	0.25	0.5	1 MW	40 MW	785	2,010	80	1,012	$112	$1,415	0.6%
									Totals	($Million)	$228,419	100%
*	Lifecycle, 10 years, 2.5% escalation, 10.0% discount rate.								≥ 3-h	duration	$126,327	**55.3%**
†	Based on potential (MW, 10 years) times average of low and high benefit ($/kW).								Intermediate		$78,471	**34.4%**
††	Values are for one year. However, storage could be used at more than one location, for similar benfits, during its life.								≤ 1-h	duration	$23,621	**10.3%**

From: "Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide ," SANDIA Report2010-0815, Feb 2010.

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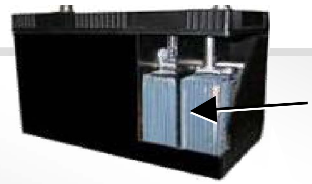
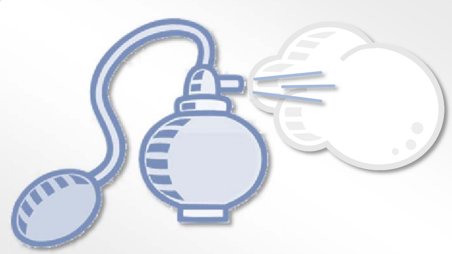
Conventional Batteries

- Everything in a single “box”
  - Plug-and-play
- A look inside the “box” reveals that:
  - Active reactants are stored in small, thin packages (*i.e.*, cells)
  - Cell “packaging” is made of:
    - Electrodes, separators, and current collectors
  - These “packaging” materials are relatively expensive
    - Corrosion resistant
    - Typically ~ ½ the cost, volume, and weight of battery



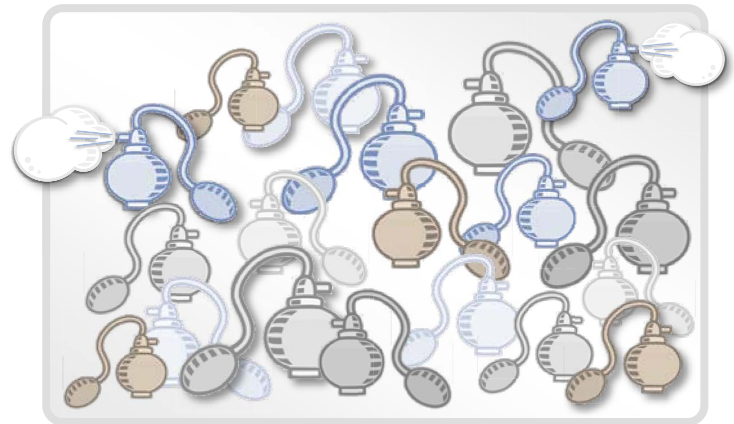
Conventional battery is composed of multiple cells

- **Ideal for portable applications**
  - Small amounts of energy
  - Very convenient package
  - Simple system



Large-Scale EES

- We want to serve applications that require large amounts of energy:
  - Need MWh, not mWh (10^6 factor)
- Fluid analogy:
  - Fluid = Energy
  - Need Gallons, not a few drops
  - Does not make sense to use ounce-size packages

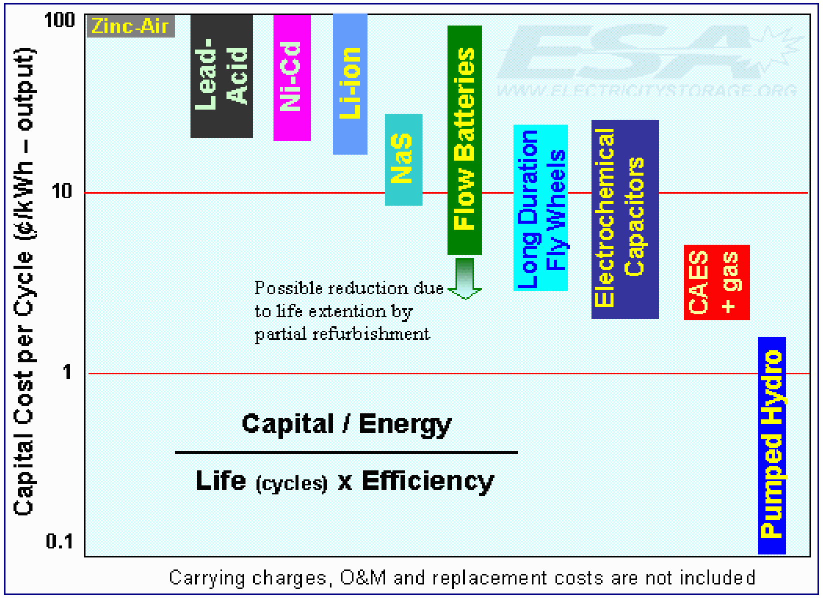


- Ideally, need batteries that can store large amounts of reactants
  - Economically
  - In drums, not small packages

Conventional battery life-cycle costs are relatively high

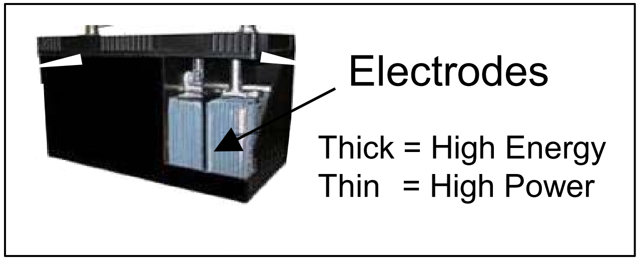
Expected to remain so due to fundamental issues

- Issues with conventional batteries:
  - Relatively short cycle life with deep discharge/charge cycles
    - Electrodes undergo physiochemical changes
  - Relatively low active-material-to-inactive-material ratios (*i.e.*, discharge times typically ≤ 1 h at rated power output)
    - Stored in small 2-D packages
  - High replacement costs (must replace essentially entire system)
  - Lower round-trip efficiency with less expensive chemistries
  - Power and energy are *not* independent
    - Cannot design a battery that can deliver both high power and high energy



Estimates of life-cycle costs for state-of-the-art EES technologies (note this is capital cost only).
Source: Electricity Storage Association website

Note:
- Flywheels and capacitors are short-discharge time devices
- CAES and pumped hydro are geographically constrained

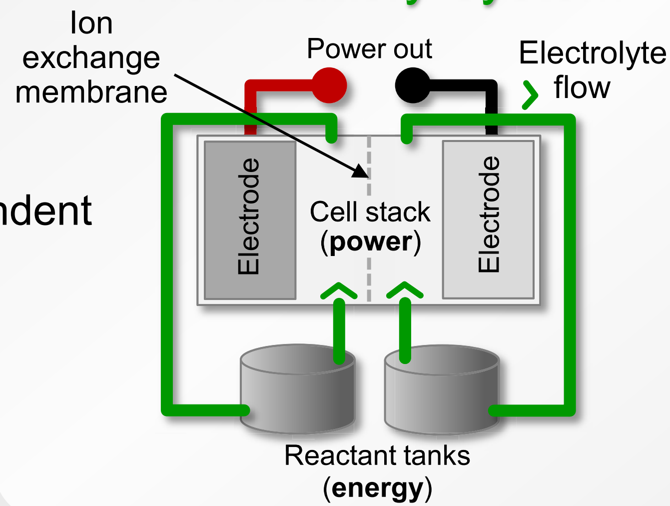


- Leading battery technologies for grid-scale applications with multiple-hour discharge
  - Flow batteries & liquid-electrode batteries
    - Extended discharge times
    - Lower inactive material per active material
    - Long cycle life, even with deep discharges

Flow Batteries are essentially rechargeable fuel-cell systems

Combine the best attributes of rechargeable batteries and fuel cells

Flow Battery System



Cell stack attributes

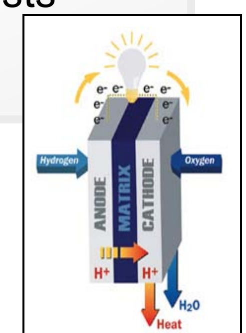
- Energy and power independent
- Long life cycle
- Low self-discharge rates

Battery attributes

- Rechargeable
- High round-trip efficiencies
- No precious-metal catalysts

Fuel cell issues (for energy storage)

- Low round-trip efficiencies
- Precious-metal catalysts
- Hydrogen storage



Conventional battery constraints

- High power OR High energy
- Limited life cycle
- Continuous self-discharge

Flow Battery Systems (FBS) have been demonstrated in field

Technology is proven, but not cost effective

- Flow Battery concept originally developed by NASA in 1970s (Fe-Cr system)
- Multiple fielded FBS demonstrations have been done, especially with VRB (*e.g.*, Sumitomo Electric in Japan)
- Generally, successful except for Capital Cost of the System

- Example of fielded prototype unit
  - Installed by VRB Power Systems
  - 500-kW / 2-MWh plant in Moab, Utah
    - Ambient temperature range of -25 to 55+ C
    - T&D upgrade deferral in sensitive site
  - Hand-off in Mar. 2004; run unmanned thru 2009
    - Availability > 96% over 5-yr period
      - Experienced PCS card failure (lightening strike)
    - Completed > 1600 cycles

However, technology has not received much attention in last ~ 30 years, since FBS is only suitable for large-scale EES applications, and the cost targets for these applications are very challenging (i.e., lower than portable or even transportation)

Multiple types of Flow-Cell Systems for EES

Technology platform will depend on App, but all use common technologies

Flow-Cell Technology	Major attributes	Major Issues (with Current Technology)
Reversible Fuel-Cell /Electrolyzer systems (*e.g.*, H_2/O_2, H_2/Air)	Energy and power independent Long life cycle Low self-discharge rates	Complex (relative to conventional battery) Low round-trip energy efficiencies ($\leq$ 50%) Bi-functional oxygen electrode design (gas/liquid) Bi-functional oxygen electrocatalysts Precious-metal catalysts (both electrodes) Hydrogen storage (complex and/or costly)
Closed-Loop Reversible Fuel Cell systems (*e.g.*, H_2/Br_2, H_2/Cl_2)	Energy and power independent Long life cycle Low self-discharge rates	Complex (relative to conventional battery) Relatively low round-trip efficiencies ($\leq$ 60%) Precious-metal catalysts (both electrodes) Vapor pressure of Br_2 or Cl_2 Hydrogen storage(complex and/or costly)
Redox Regenerative Fuel Cell (RRFC) systems (*e.g.*, Fe/Cr, V/V, S/Br_2)	High round-trip efficiencies ($\geq$ 70%) No precious-metal catalysts Energy and power independent Long life cycle Low self-discharge rates	Complex (relative to conventional battery) Low energy density (relative to batteries) Poor cell performance (relative to PEMFC)
Hybrid Fuel-Cell/Battery systems (*e.g.*, Zn/Br_2, Zn/Cl_2, Ni/H_2)	High round-trip efficiencies ($\geq$ 70%) Low self-discharge rates Moderate energy densities	Complex (relative to conventional battery) Power & energy <u>not</u> independent (Zn or Ni plating) Limited life cycle (Zn or Ni electrode) Precious-metal catalysts(Br, Cl, or H_2 electrode) Vapor pressure of Br_2 or Cl_2; or Hydrogen storage
Hybrid Redox/Air systems (*e.g.*, $V^{2+/3+}$/Air)	Only one reactant to store Low self-discharge rates Energy and power independent	Complex (relative to conventional battery) Bi-functional oxygen electrode design (gas/liquid) Bi-functional oxygen electrocatalysts Precious-metal catalysts (O_2 electrode)
Hybrid H_2/Redox systems (*e.g.*, $H_2/Fe^{2+/3+}$, $H_2/V^{4+/5+}$)	High round-trip efficiencies ($\geq$ 70%) Low self-discharge rates Moderate energy densities Energy and power independent	Complex (relative to conventional battery) Low energy density (relative to batteries) Some precious-metal catalysts (H_2 electrode) Hydrogen storage

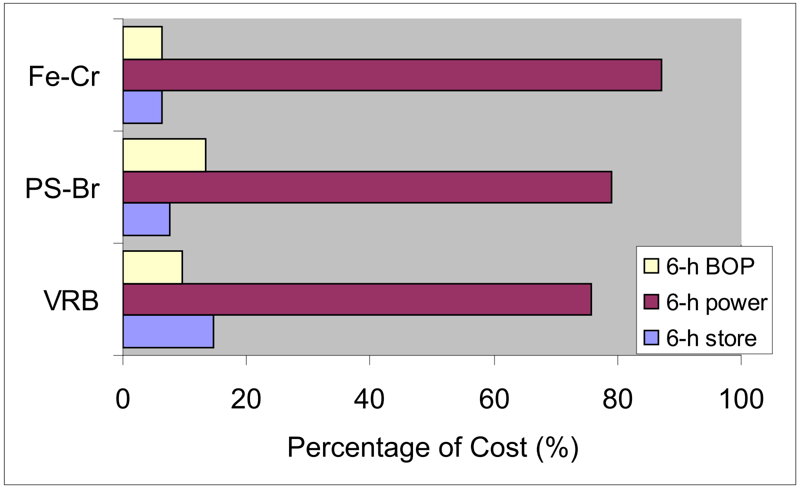
- Both Hydrogen and Oxygen are good reactants for flow-cell systems
- Air is ideal reactant, from storage perspective, but relatively low round-trip efficiency
- Hydrogen offers high round-trip efficiency, but challenge is hydrogen storage

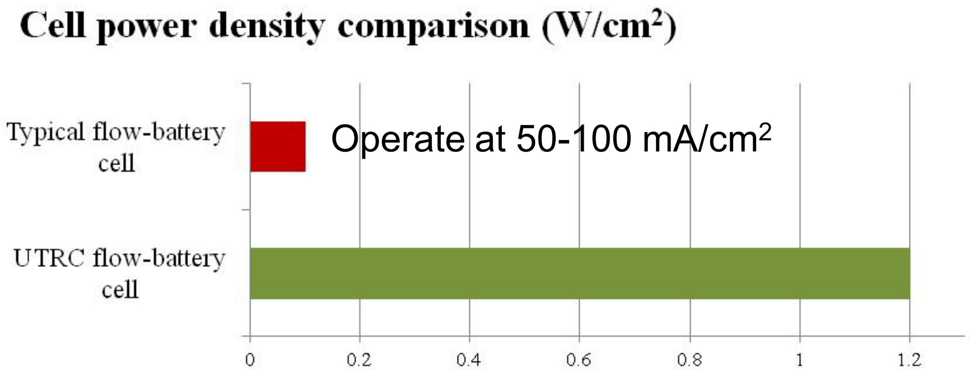
Flow-Battery System Cost is Dominated by Stack

Major focus of UTRC's ARPA-E project is to substantially reduce stack cost

- FBS has 3 major sub-systems:
  1. Power module (Stack), $/kW
     - Custom reactor built from custom components
     - Electrodes, separators, and current collectors
  2. Reactant storage, $/kWh
     - Redox couples dissolve in aqueous solution
     - Plastic tanks
  3. Balance of Plant (BOP), $/kW
     - Pumps + plastic plumbing
     - Controller
     - Power Electronics

- If Stack cost can be reduced by a factor of ~ 4X, then Flow-Battery System cost can be cut in half





- Cell performance results shown are for VRB cells
- Improvements obtained using *conventional materials*

Cell Power Density

- Increasing power density means further decreasing non-active/active material ratio
  - Can do much better than conventional batteries (due to forced convection)

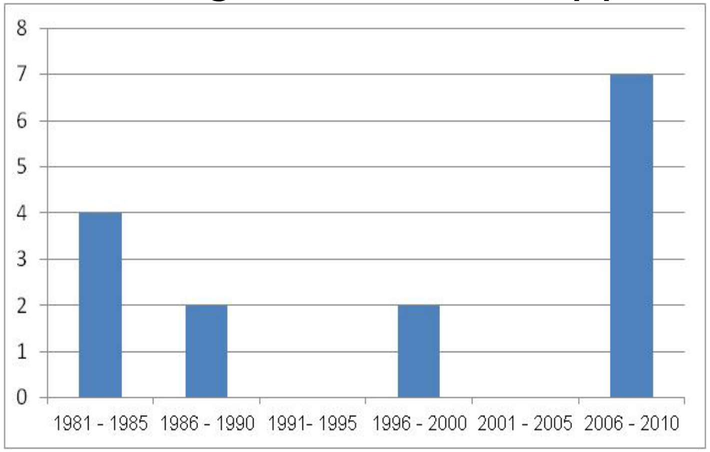
- Fluid Analogy
  - Power = Flow Rate
  - Conventional flow-battery stacks are like atomizers
    - Deliver power at low rates

- Many required to deliver significant flow of fluid
  - Many, or large, stacks required
- We need *Nozzles*!

Summary

Flow-Battery Systems offer many advantages for large-scale EES apps

- Key Benefits:
  - Both High Energy and High Power
  - Good round-trip energy efficiencies (~ 75-80%)
  - Long cycle life (> 10K)
  - High utilization of active materials (~ 90%)
  - Minimize non-active materials (especially for high energy apps)
- Technology is proven, but not (yet) cost effective
- Lots of future potential
  - Limited development over the past three decades
  - Fuel-cell developers well suited to transform FBS technology



Number of papers appearing in peer-reviewed *Electrochemical Society* publications that have the terms “flow battery,” “redox battery,” or “redox fuel cell” in the title or abstract

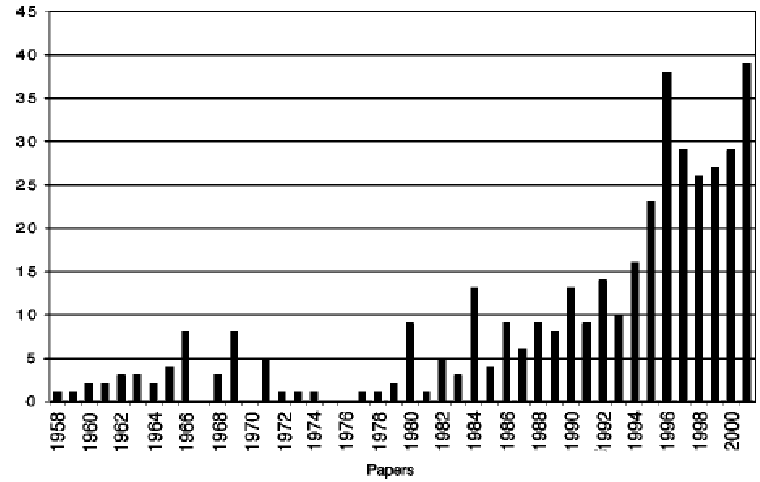


Figure 3. The number of papers appearing in the Journal which include the phrase “fuel cell” in the title.

M. Perry & T. Fuller, “A historical perspective of fuel-cell technology in the 20th Century,” *Journal of the Electrochemical Society*, **V149**, S59 (2002).

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