Clean Energy States Alliance

Energy Storage Technology Advancement Partnership (ESTAP) Webinar:

Flow Battery Basics, Part 1: What They Are, How They Work, & Where They're Used

June 19, 2014

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

State & Federal Energy Storage Technology Advancement Partnership (ESTAP)

Todd Olinsky-Paul
Project Director
Clean Energy States Alliance

Thank You:

Dr. Imre Gyuk
U.S. Department of Energy,
Office of Electricity Delivery and
Energy Reliability

Dan Borneo
Sandia National Laboratories

ESTAP is a project of CESA

Clean Energy States Alliance (CESA) is a non-profit organization providing a forum for states to work together to implement effective clean energy policies & programs:

- Information Exchange
- Partnership Development
- Joint Projects (National RPS Collaborative, Interstate Turbine Advisory Council)
- Clean Energy Program Design & Evaluations
- Analysis and Reports

CESA is supported by a coalition of states and public utilities representing the leading U.S. public clean energy programs.

Clean Energy States Alliance

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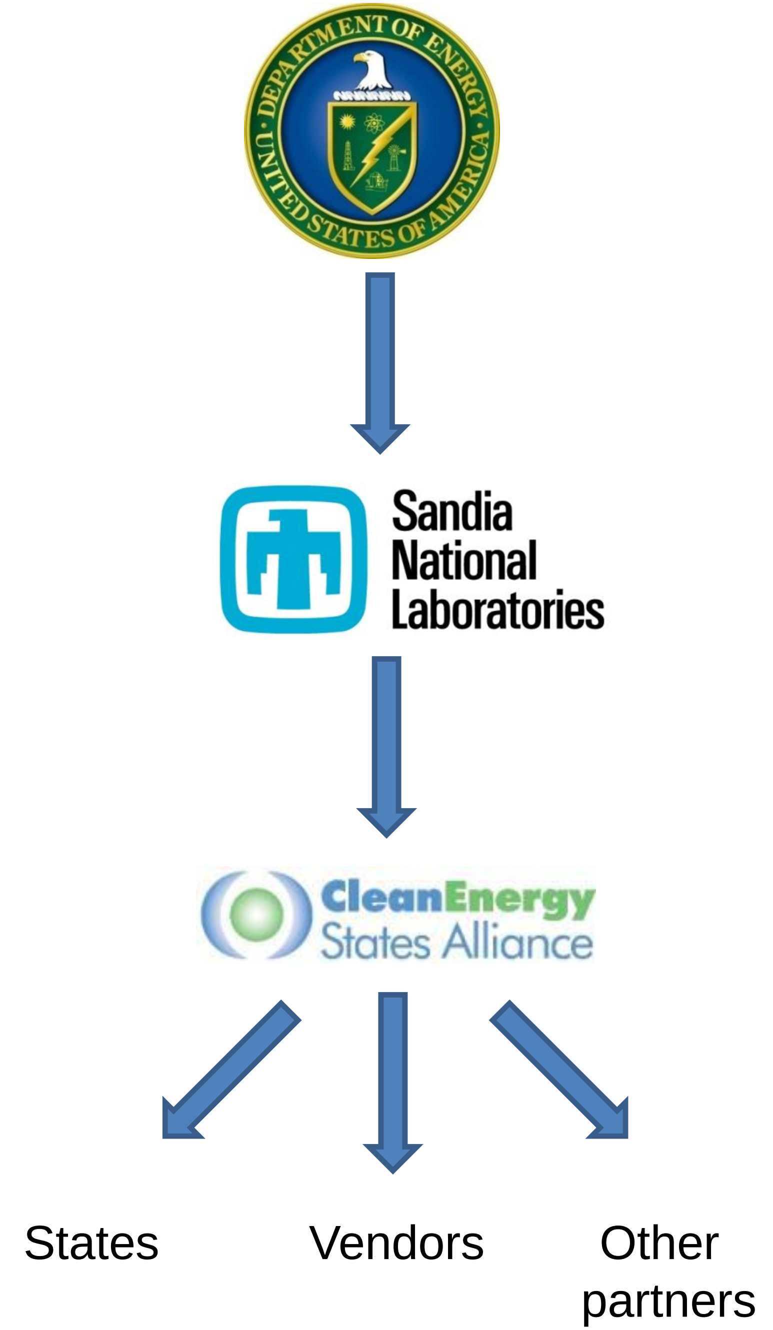
U.S. DEPARTMENT OF ENERGY

ESTAP* Overview

Purpose: Create new DOE-state energy storage partnerships and advance energy storage, with technical assistance from Sandia National Laboratories

Focus: Distributed electrical energy storage technologies

Outcome: Near-term and ongoing project deployments across the U.S. with co-funding from states, project partners, and DOE



* (Energy Storage Technology Advancement Partnership)

ESTAP Key Activities

1. Disseminate information to stakeholders
   - ESTAP listserv >500 members
   - Webinars, conferences, information updates, surveys
2. Facilitate public/private partnerships at state level to support energy storage demonstration project development
   - Match bench-tested energy storage technologies with state hosts for demonstration project deployment
   - DOE/Sandia provide $ for generic engineering, monitoring and assessment
   - Cost share $ from states, utilities, foundations, other stakeholders

ESTAP Webinars

Policy Webinars:

- Introduction to the Energy Storage Guidebook for State Utility Regulators
- Briefing on Sandia's Maui Energy Storage Study
- The Business Case for Fuel Cells 2012
- State Electricity Storage Policies
- Highlights of the DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA

Technology Webinars:

- Smart Grid, Grid Integration, Storage and Renewable Energy
- East Penn and Ecoult Battery Installation Case Study
- Energy Storage Solutions for Microgrids
- Applications for Redox Flow Batteries
- Introduction to Fuel Cell Applications for Microgrids and Critical Facilities
- UCSD Microgrid

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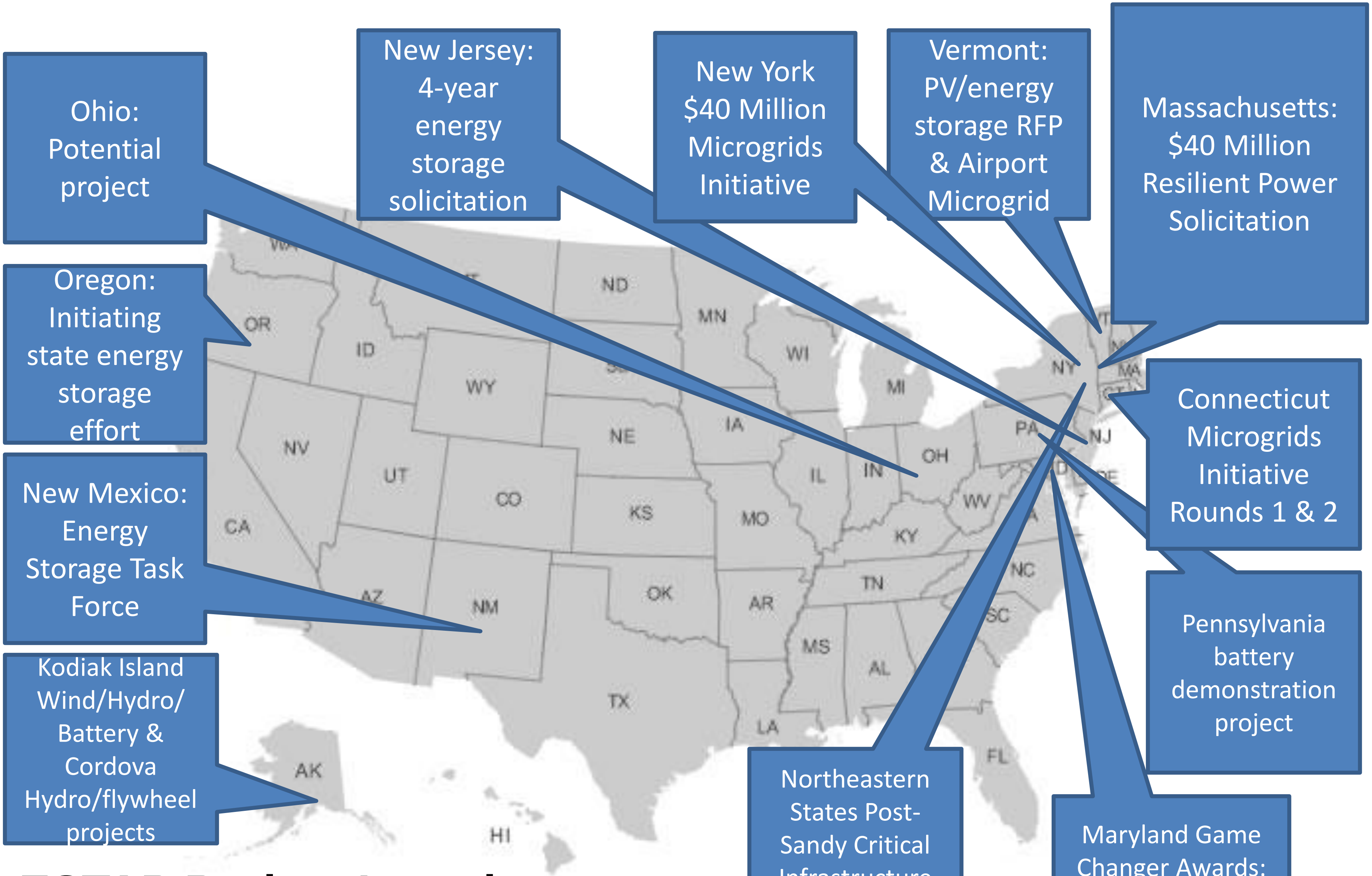


ESTAP Project Locations

Clean Energy States Alliance

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

Today's Guest Speakers

Imre Gyuk, Program Manager, Energy Storage Research, Office of Electricity Distribution and Energy Reliability, U.S. Department of Energy

Dan Borneo, Engineering Project Manager, Distributed Energy/ Electrical Energy Storage, Sandia National Laboratories

Summer Ferreira, Senior Member of Technical Staff, Sandia National Laboratories

Charlie Vartanian, Marketing Director, UniEnergy Technologies (UET)

Craig Horne, Chief Strategy Office and Co-Founder, EnerVault

Flow Batteries for Bulk Energy Storage

IMRE GYUK, PROGRAM MANAGER
ENERGY STORAGE RESEARCH, DOE

ESTAP 06-19-14

Flow Batteries decouple Power from Energy:

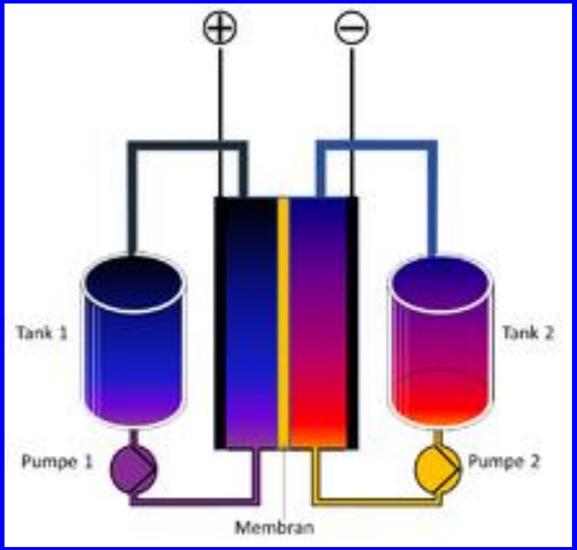
- Power is produced by a rechargable Electrochemical Cell

- Energy is stored in Tanks of electrolyte

This is analogous to a car:

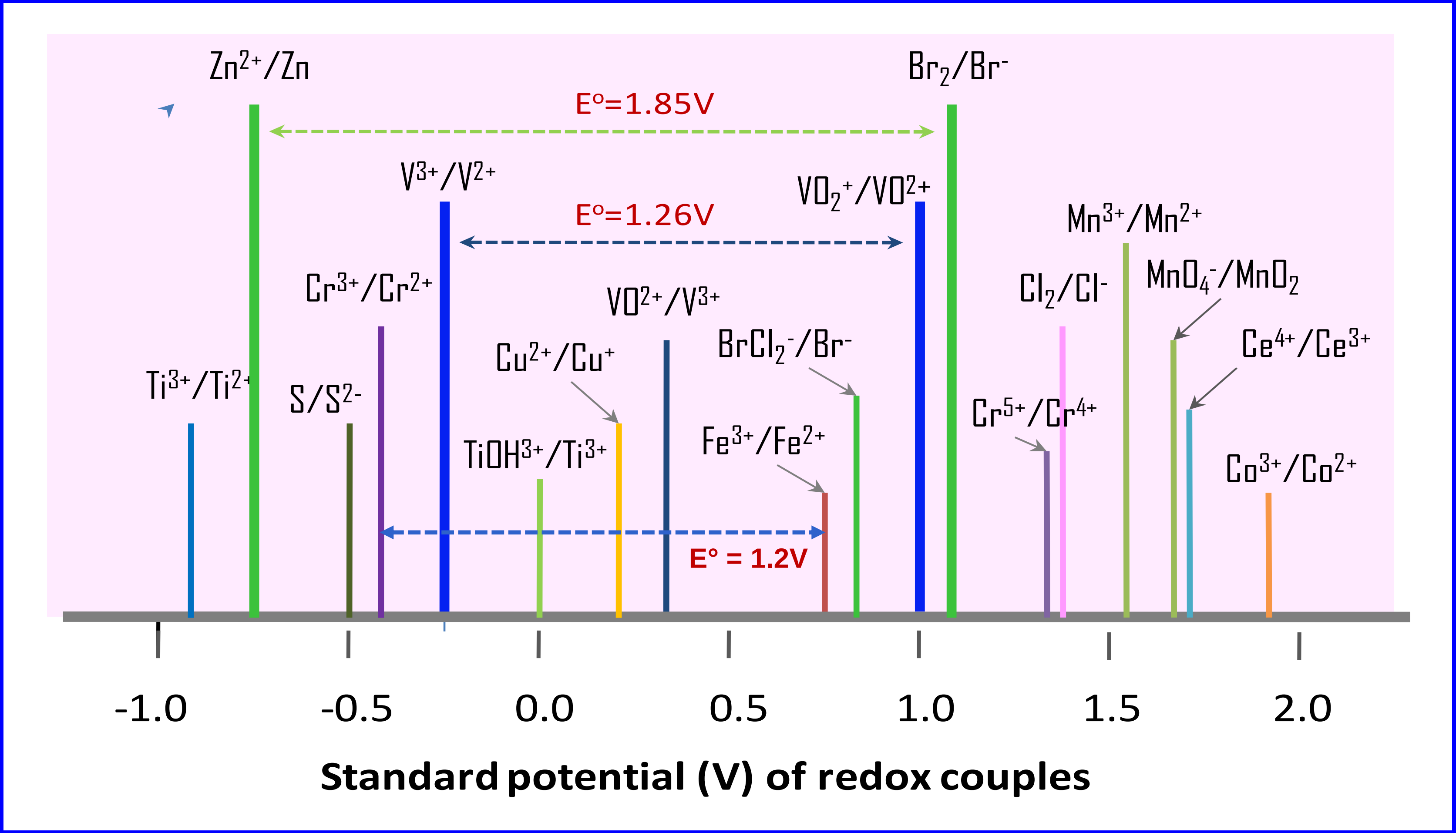
- Power comes from the Engine

- Energy is in the gasoline Tank

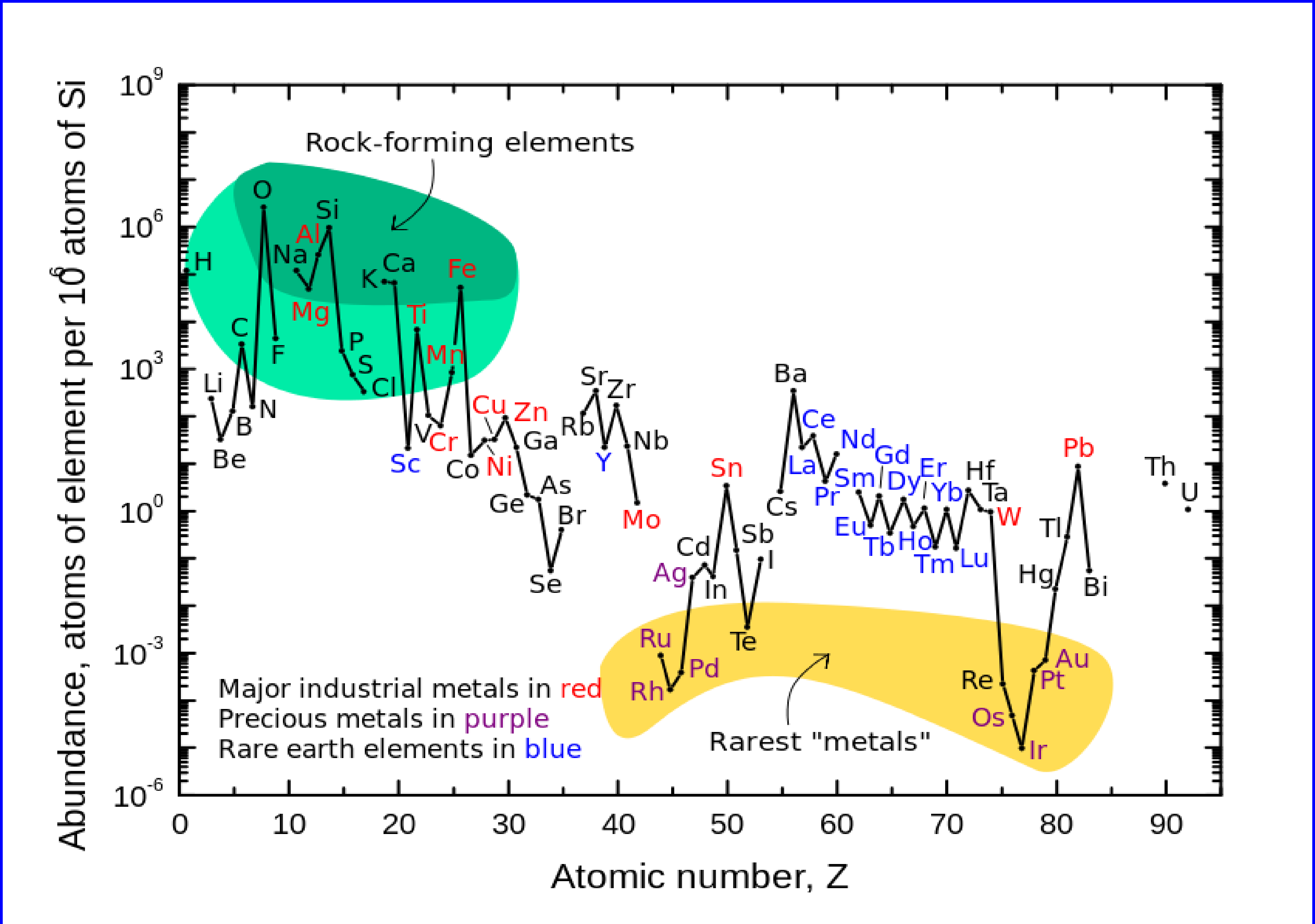


The Periodic Table

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	$\boxed{\text{30 Zn}}$	31 Ga	32 Ge	33 As	34 Se	$\boxed{\text{35 Br}}$	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	



We want high Potential !



We want low Cost !

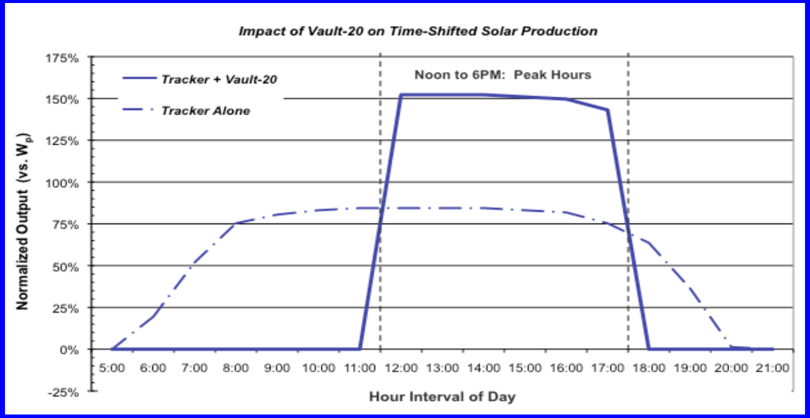
ARRA - Enervault:

250kW/4hr   Fe-Cr Flow Battery

PV: 300 kW
Storage: 250 KW
Peak output: 450kW
Storage Cost: +16%
Storage Value: +84%
Commissioned May 22, 2014

Tracking PV in Almond Grove

Installation of Tanks at Turlock



Leveraging PV with Storage

Washington State Clean Energy Fund:

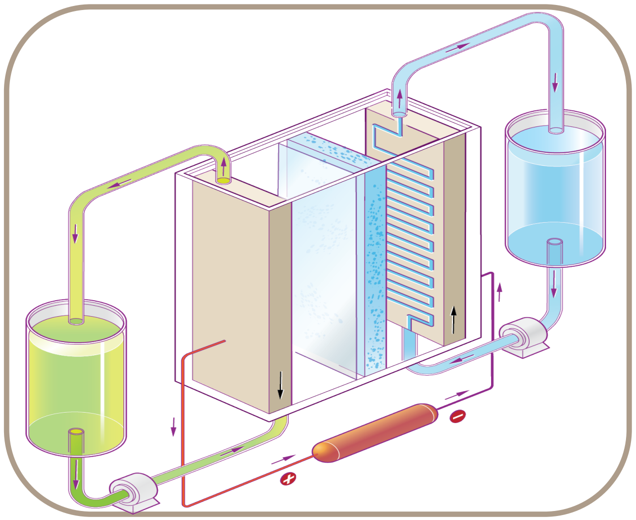
Solicitation for $15M for Utility Energy Storage Projects

Submitted Projects with UET V/V technology:

- Snohomish PUD (2MW / 6.4MWh) – PNNL -- U of WA
- Avista (1MW / 3.2MWh) – PNNL -- 1 Energy -- WA State

UET V/V technology was developed at PNNL with DOE-OE funding

PNNL will participate in both Proposals, with benefit optimization studies.



Flow Batteries

Introduction to flow batteries

Clean Energy States Alliance Webinar June 19, 2014

Summer R. Ferreira, Travis M. Anderson, Org. 2546, Advanced Power Sources R&D

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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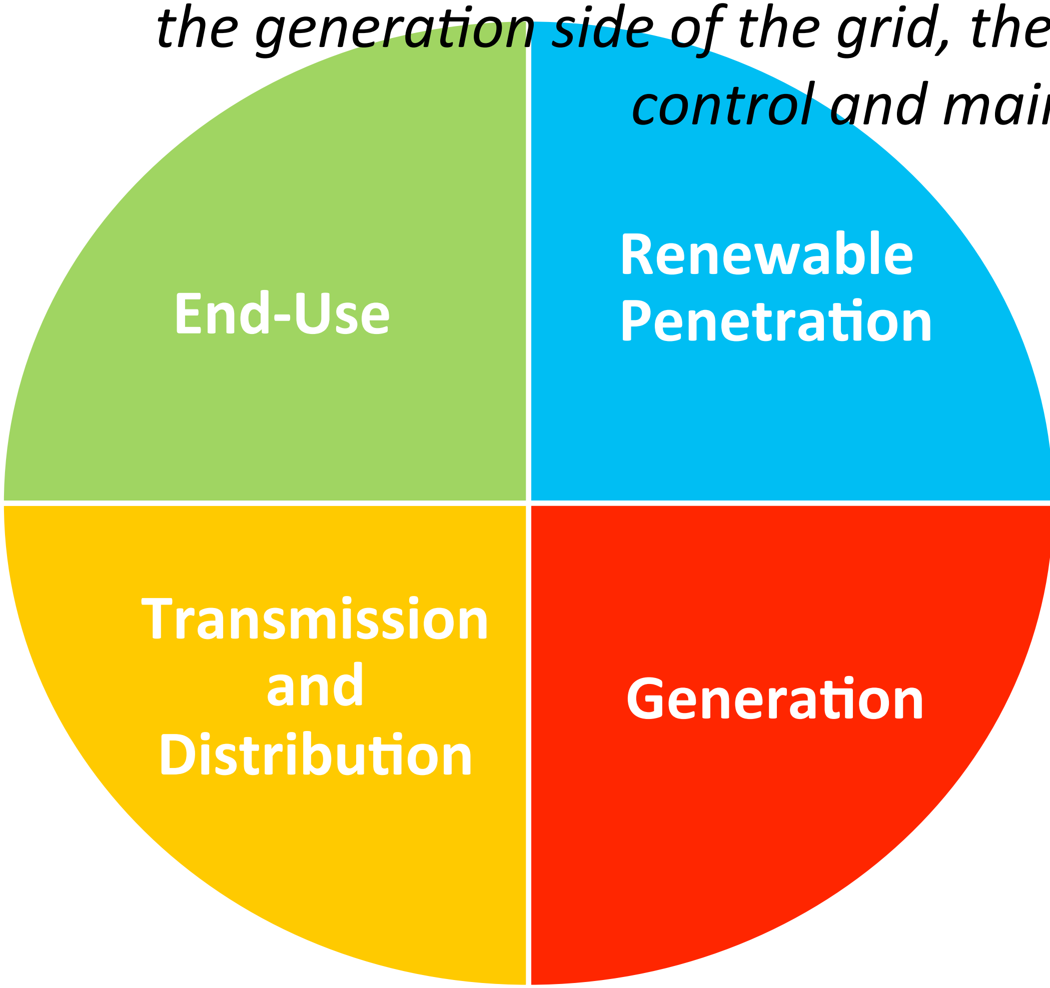
Energy Storage Services

*"Storage is a vital tool that would uncouple customer demand from the generation side of the grid, thereby allowing vital flexibility in control and maintenance of the electric grid."**



- **Reduce carbon footprint**
- **Provide buffer for the grid**
- **Smart grid integration**

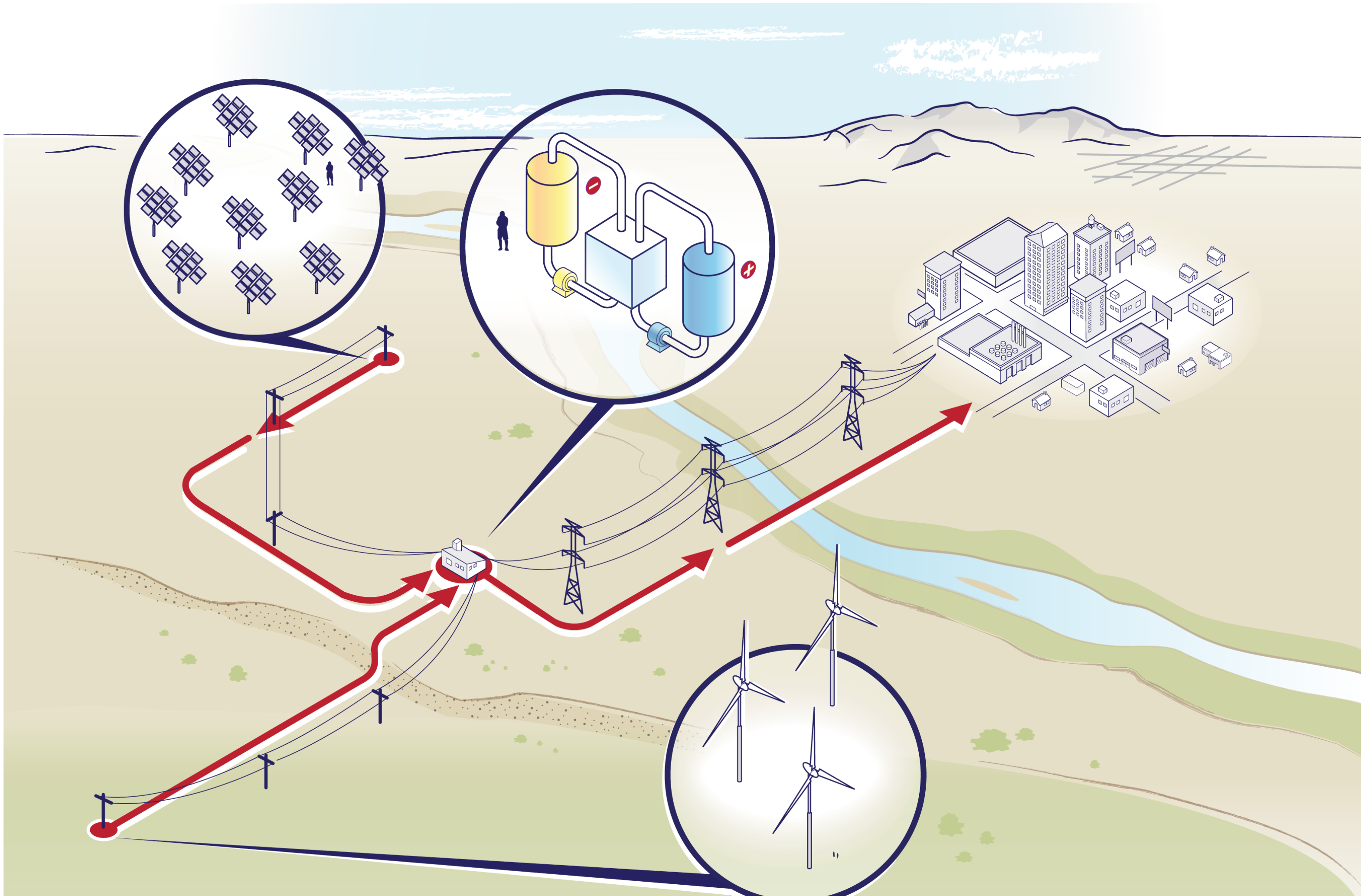
Costs are the main barrier

Stationary Storage

Technology	Power rating	Discharge Duration (h)	Cost ($/kWh)	Cycle life
Pumped Hydro	10's MW - GWs	>8	80-200	20,000-50,000
CAES	10's MW - GWs	0.25	50-120	9,000-30,000
Lead-acid batteries	kw -10's MWs	0.1-4	350-1500	200-1,500
Li ion batteries	kW-100's MW	0.1-1	850-5000	5,000-7,000
Flow batteries	kW-100's MW	1-20	180-250	5,000-14,000+

Journal of The Electrochemical Society, 158 (8) R55-R79 (2011) and
http://www.purdue.edu/discoverypark/energy/assets/pdfs/SUFG/publications/SUFG%20Energy%20Storage%20Report.pdf

Flow Batteries and Renewables

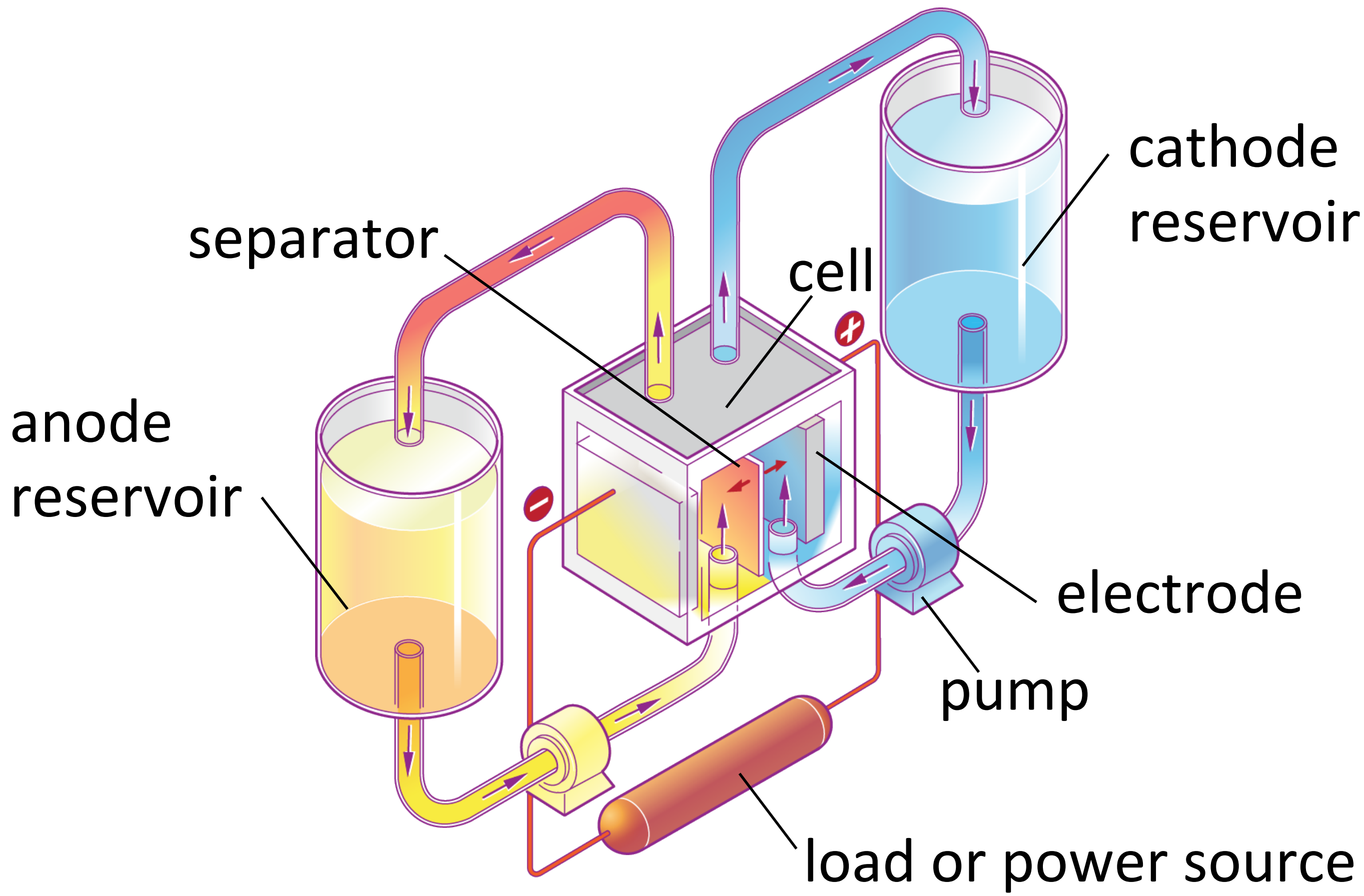


Long cycle life   Deep discharge ability   Easy scalability

Flow batteries decouple energy and capacity.

Flow Battery

- energy storage technology utilizing redox states of various species for charge/discharge purposes

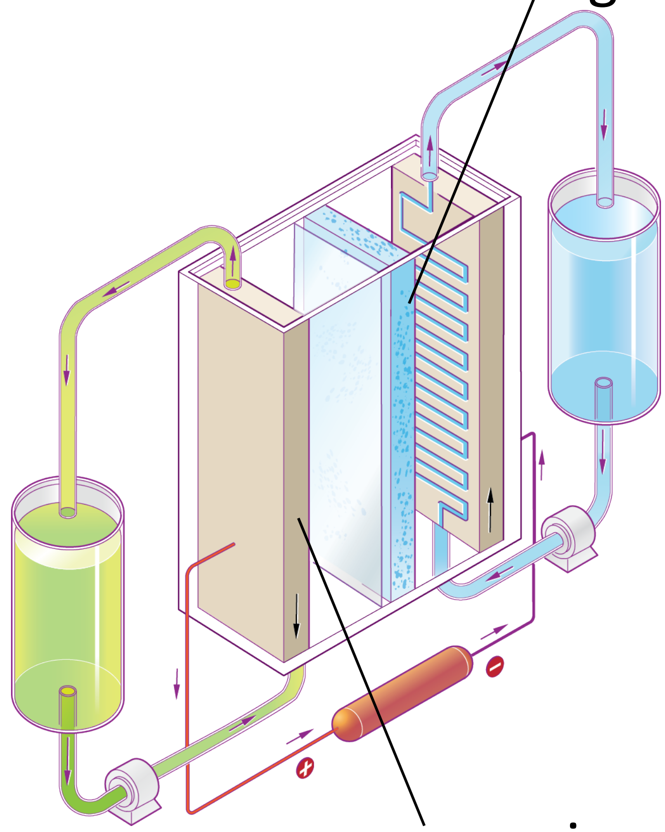


The “fish tank” schematic does not represent a specific chemistry.

Early Development

Open Circuit
Potential (OCP)
1.2 V

significant crossover



$Fe^{2+} \rightleftharpoons Fe^{3+} + e^-$

$Cr^{2+} \rightleftharpoons Cr^{3+} + e^-$

requires electrocatalyst

Zn/Cl hydrate battery in 1968[1]
Fe/Cr RFB in the 1970s[2]

[1]Linden's Handbook of Batteries [2]J Appl Electrochem (2011) 41:1137–1164

All-Vanadium Battery

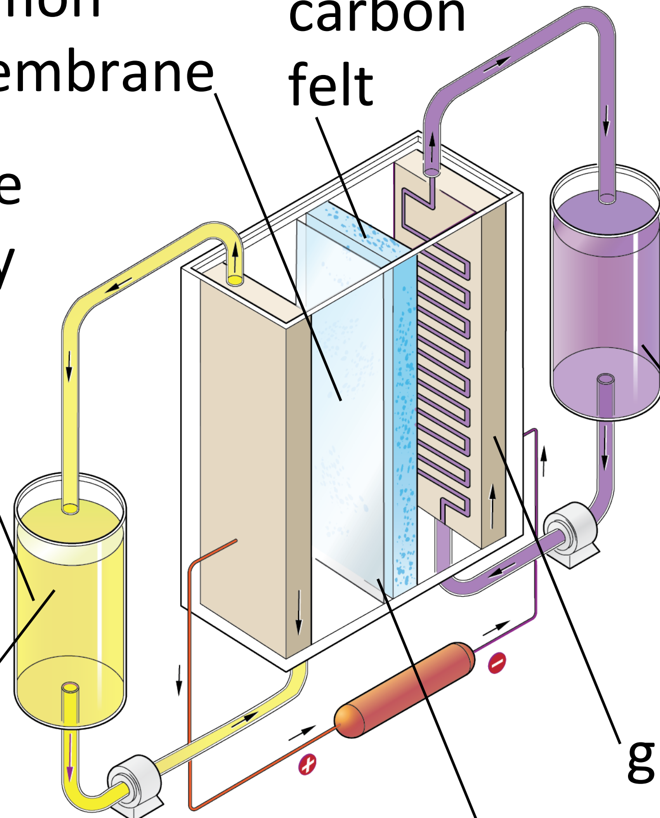
Sandia National Laboratories

Nafion® membrane

carbon felt

Open Circuit Potential (OCP) **1.5 V**

electrolytes influence temperature stability and vanadium concentration



$V^{2+} \rightleftharpoons V^{3+} + e^{-}$

low vanadium concentration/low energy density

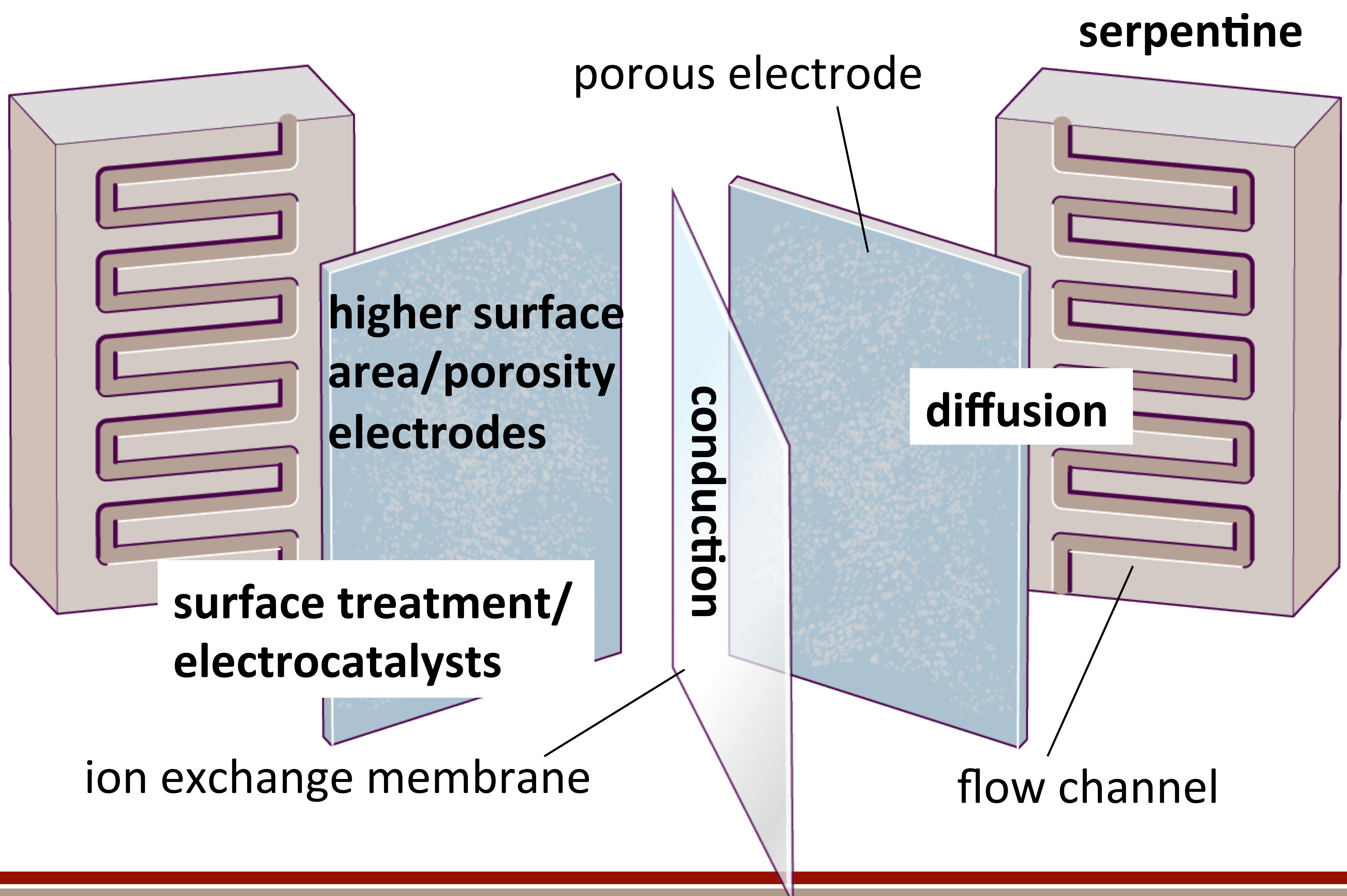
temperature sensitivity

graphite

$VO^{2+} + H_2O \rightleftharpoons VO_2^{+} + e^{-}$

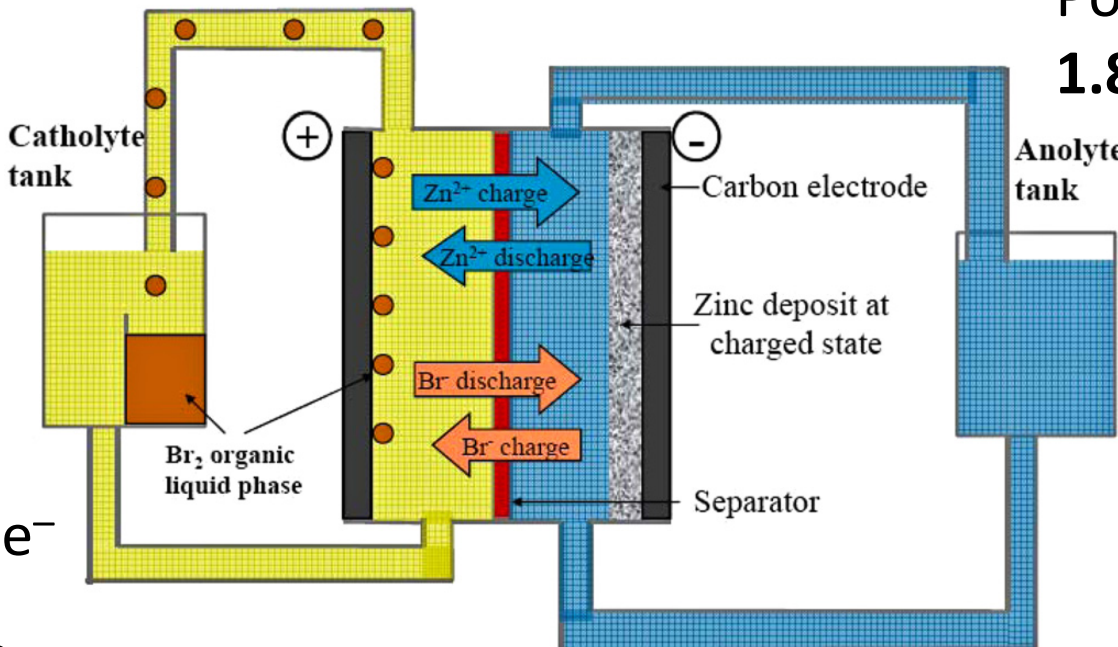
crossover is less of an issue

Cell Configuration



Hybrid Flow Batteries

Open Circuit Potential (OCP)
1.8 V



$$2X^- \rightleftharpoons X_2 + 2e^-$$

X = Cl or Br

$$Zn^0(s) \rightleftharpoons Zn^{2+} + 2e^-$$

Higher energy density than the all-vanadium system at the expense of toxicity, dendrite formation, higher self-discharge, plate stripping required

Sandia's OE Portfolio in Flow Batteries

Research enables applied analysis, applied analysis enables research.
The goal is to assist toward greater deployment on the grid.

Research ⟺ **Applied Analysis**

Membrane Development

- Separators/membranes identified as high-cost bottleneck

Battery Modeling

Non-Aqueous Chemistries

Power System Reliability

Control algorithms

System testing

Demonstration Projects

Grid-Level Integration Analysis

Regulatory and Policy Analysis

Demonstrations of flow battery technologies since the 1980s and 1990s. More installations and larger projects are being seen.

Acknowledgments

- Dr. Imre Gyuk, Energy Storage Program, Office of Electricity Delivery and Energy Reliability
- Sean Hearne, Program Manager
- Miles Hall, Economics
- Chris Brigman, Sandia Creative Arts

EnerVault

Safe, Reliable, Cost-Effective Energy Storage

LONG-DURATION, GRID-SCALE IRON-CHROMIUM REDOX FLOW BATTERY SYSTEMS

Craig R Horne, Ph.D.

Chief Strategy Officer & Co-Founder

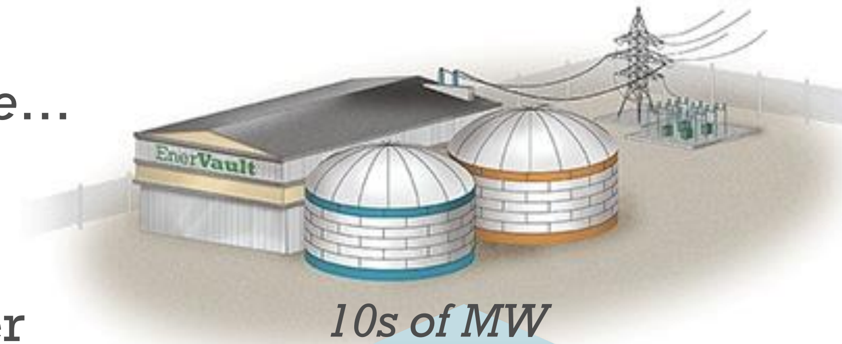
ESTAP Webinar

EnerVault
Safe, Reliable, Cost-Effective Energy Storage

Company Overview

Focus:

Long-duration, grid-scale energy storage…



Distinction:

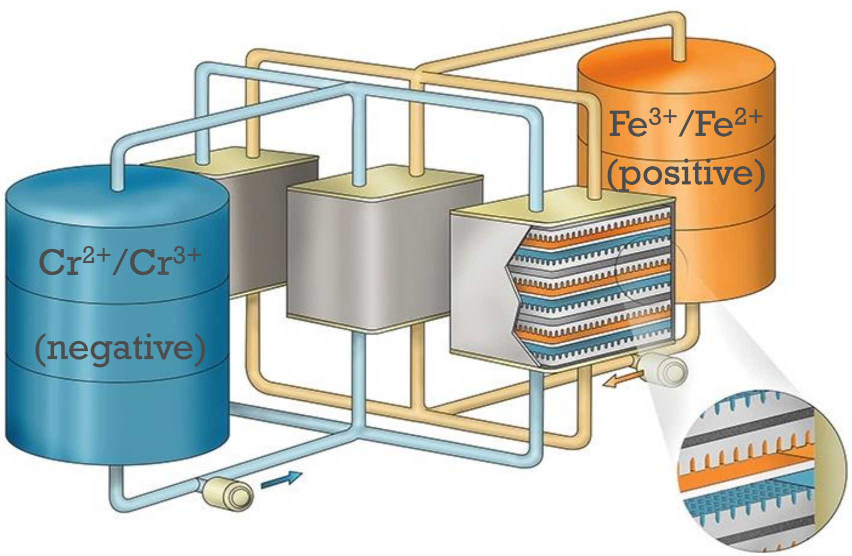
Long duration storage at constant power

Unparalleled safety, reliability, and low cost

Configurable & scalable design optimizes costs

10s of MW
100s of MW-hr

250 kW_{AC}
4 hour



International Network And Wide Recognition

EnerVault
Safe, Reliable, Cost-Effective Energy Storage

Supported by leading global corporations and funding agencies

investors

TOTAL

MITSUI GLOBAL INVESTMENT

EREN Group

3M

OCEANSHORE VENTURES

TEL TOKYO ELECTRON

CE COMMERCIAL ENERGY
Your Best Choice

recognition & associations

theguardian cleantech
Global Cleantech 100 '12
we're on the list.

ESA Energy Storage Association

ADVANCED ENERGY ECONOMY

GoingGreen 2011 Global 200 -WINNER-

Going Green Silicon Valley 100 Winner

UTILITY TECHNOLOGY CHALLENGE
TOP UTILITY SOLUTION

CalCharge

CESA
CALIFORNIA ENERGY STORAGE ALLIANCE

BVES
BUNDESVERBAND ENERGIESPEICHER

grant awards

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

STATE OF CALIFORNIA ENERGY COMMISSION

nyserda
Energy. Innovation. Solutions.

partners

NORAM

ASCENSION INDUSTRIES

JKB ENERGY
CAPTURING THE POWER OF NATURE

Sandia National Laboratories

DNV·GL

Raytheon Ktech

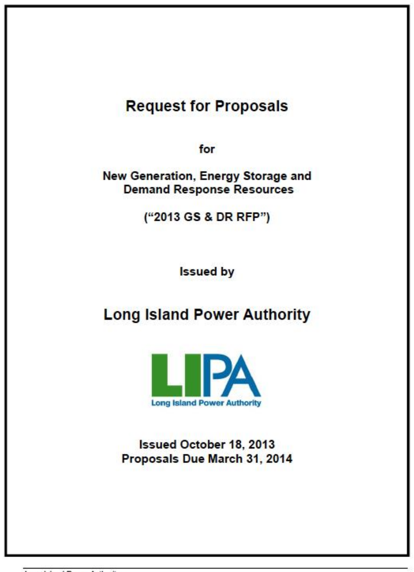
BEW Engineering (CA)

Applications - $1B in Procurements Underway!

EnerVault
Safe, Reliable, Cost-Effective Energy Storage

Peak Capacity +

12-50 MW/4 to 12 hrs



Request for Proposals

for

New Generation, Energy Storage and Demand Response Resources

("2013 GS & DR RFP")

Issued by

Long Island Power Authority

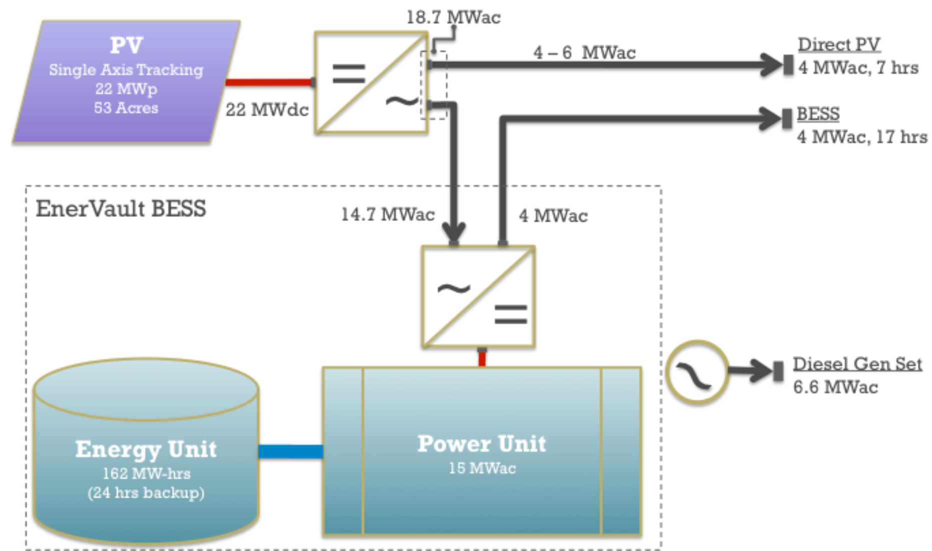
LIPA
Long Island Power Authority

Issued October 18, 2013
Proposals Due March 31, 2014

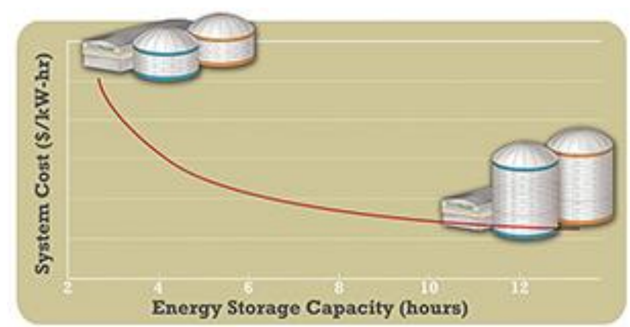
Long Island Power Authority

Clean Resilient Systems

2 to 75 MW/6 to 48 hours



Configurable energy & power capacity plus low-cost energy capacity ➔ *CapEx curve matches value curve*



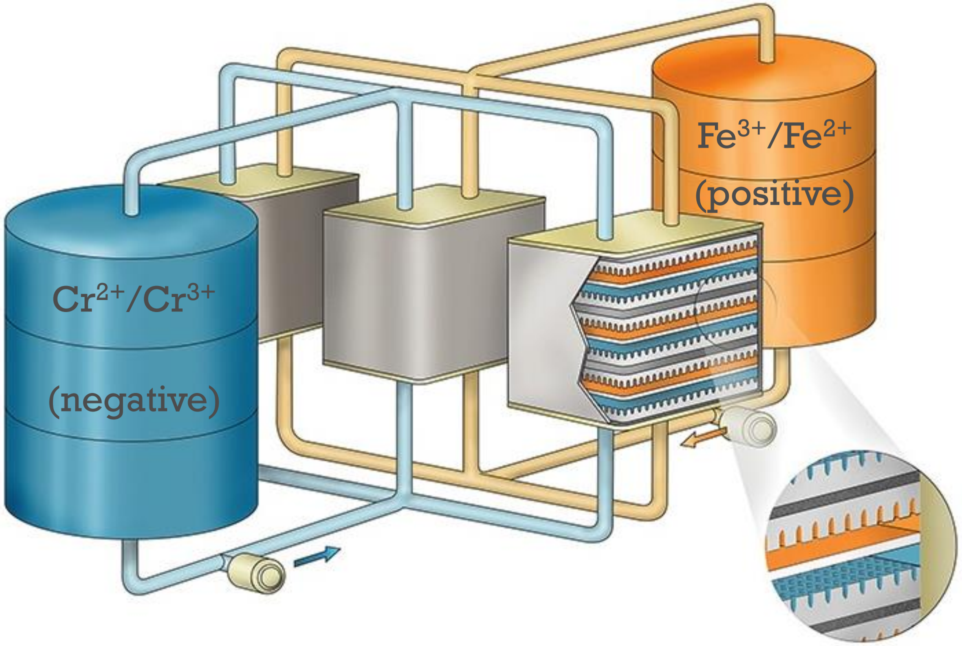
Iron-chromium Redox Flow Battery

First studied by NASA in 70s/80s

- low cost
- robust
- abundant
- safe

EnerVault

- novel architecture for sustained power
- innovations that make Fe/Cr commercial



Discharge reaction

$Cr^{2+} \rightarrow Cr^{3+} + e^-$

$Fe^{3+} + e^- \rightarrow Fe^{2+}$

Charge reaction

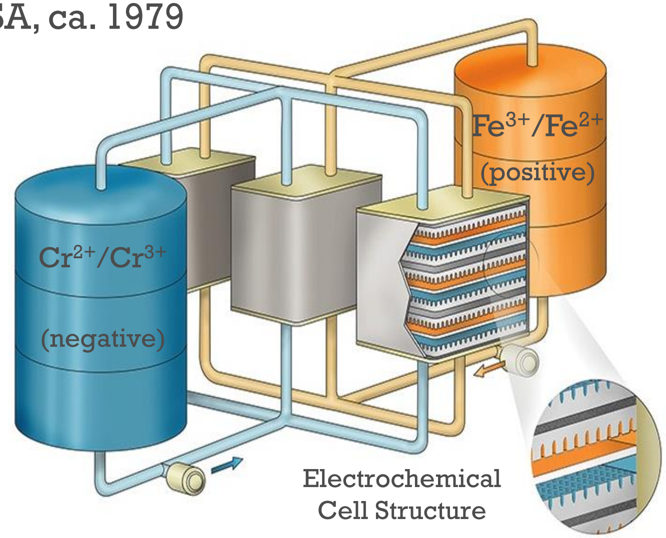
$Cr^{3+} + e^- \rightarrow Cr^{2+}$

$Fe^{2+} \rightarrow Fe^{3+} + e^-$

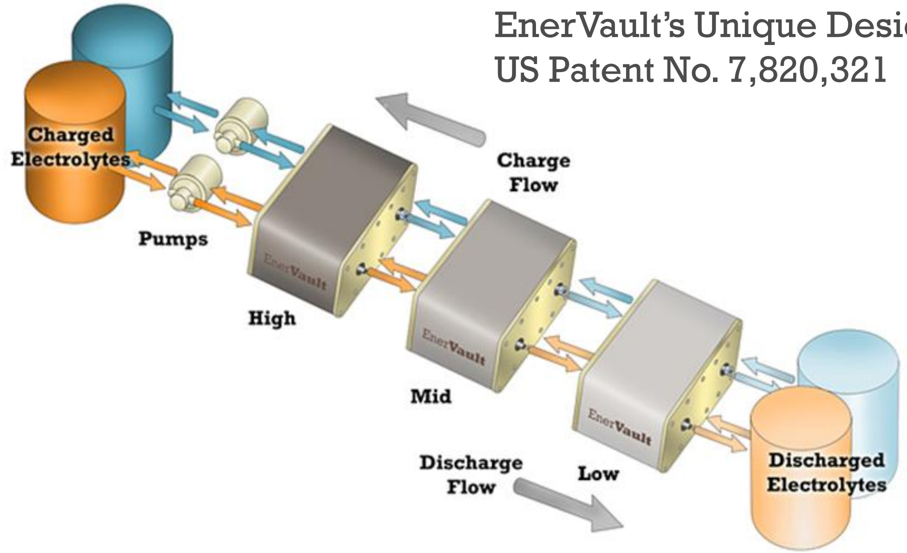
Redox Flow Battery Architectures

EnerVault
Safe, Reliable, Cost-Effective Energy Storage

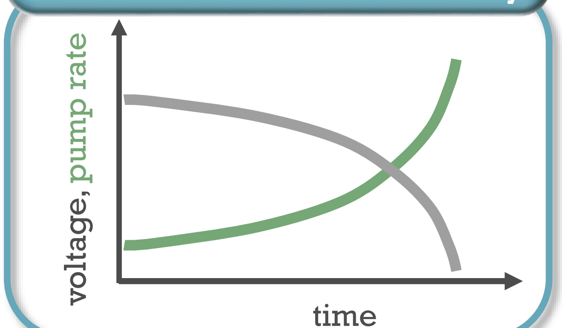
NASA, ca. 1979



EnerVault's Unique Design
US Patent No. 7,820,321

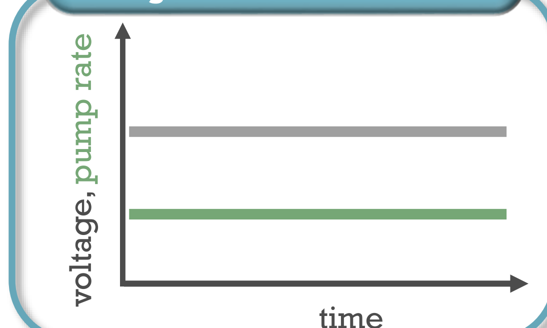


Traditional Redox Flow Battery



- Fast response to power change
- Narrow state of charge range
- Lower Efficiency

Engineered Cascade™

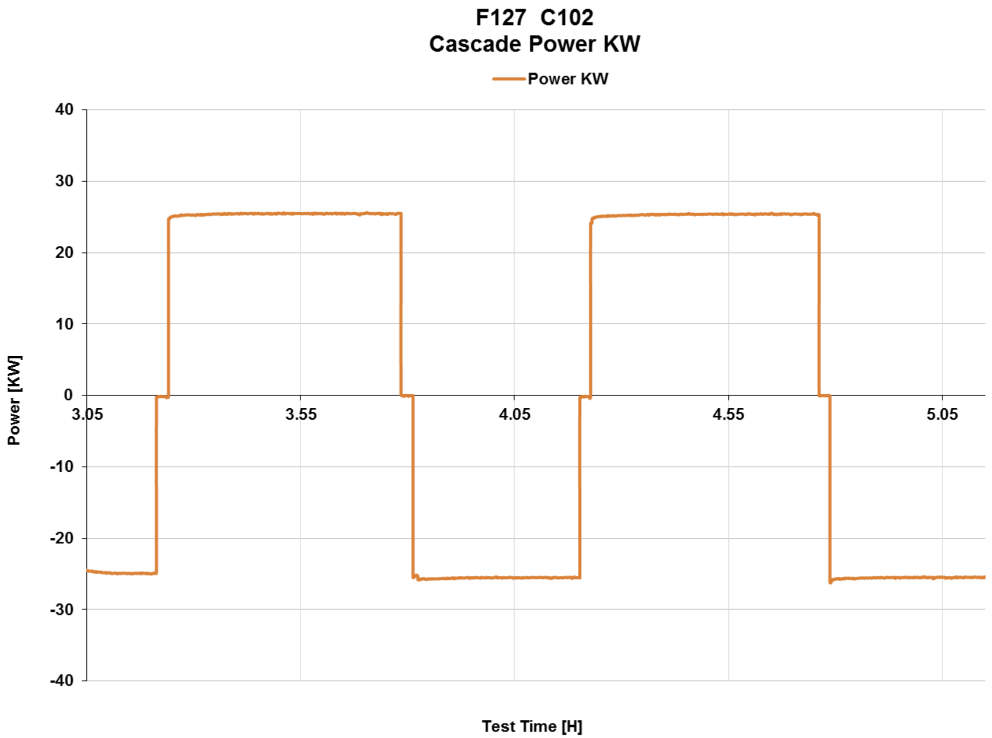


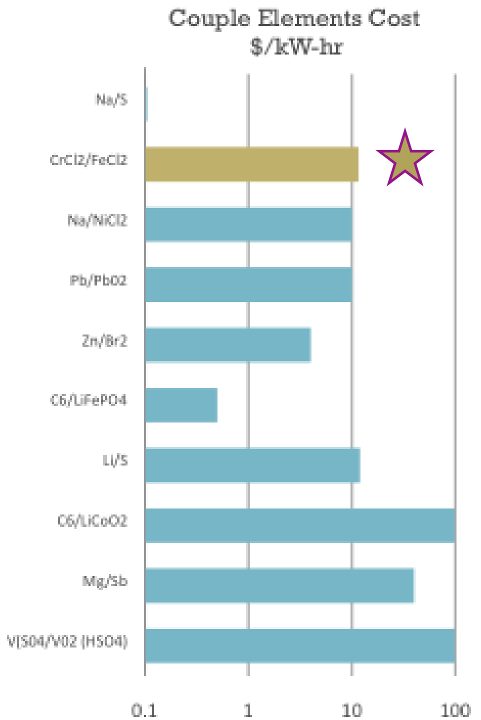
- Long duration steady power
- Wide state of charge range
- Higher Efficiency

Product Characteristics

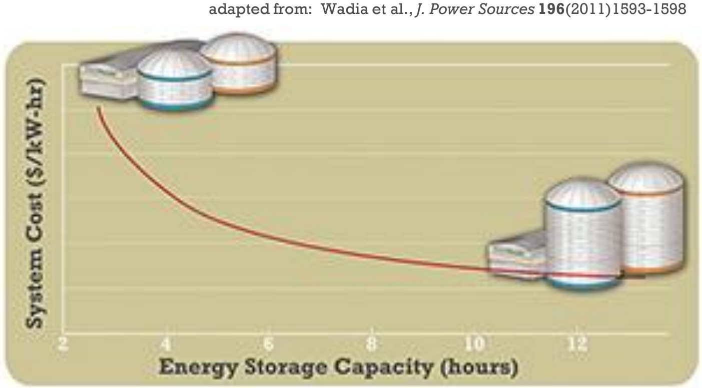
EnerVault
Safe, Reliable, Cost-Effective Energy Storage

Duration extended by simply increasing electrolyte volume





adapted from: Wadia et al., *J. Power Sources* **196**(2011)1593-1598



Configurable energy & power capacity plus low-cost energy capacity

➔ ***CapEx curve matches value curve***

Delivered Fe/Cr Technology To The Field

EnerVault
Safe, Reliable, Cost-Effective Energy Storage

2014

10X

2012

30 kW Pilot System

$250\ kW_{AC}/1$ MW-hr
Turlock Field System

2010

10X

2 kW/1 hr Test Unit

MW-hr Field Unit

EnerVault
Safe, Reliable, Cost-Effective Energy Storage

see highlights at:

http://enervault.com/enervault-turlock-dedication

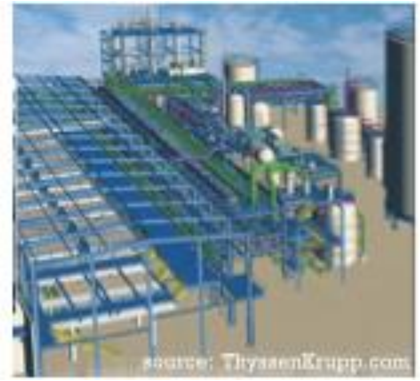
"Redox flow batteries may hold great potential for replacing gas-fired peaking power plants, and for providing badly needed grid stabilization services."

Peter Kelly-Detwiler, Forbes

Bringing Fe/Cr Systems To Market

EnerVault
Safe, Reliable, Cost-Effective Energy Storage

Leverage electrochemical process industry expertise…

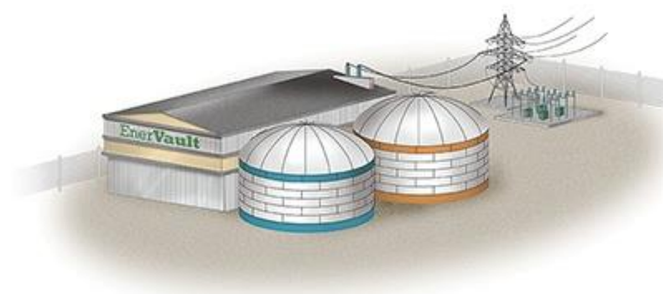


2014 → **2015** → **2016**

Demonstrate 250 kW_{AC}
1 MW-hr Field System

Deliver 1-2 MW_{AC}
IS Systems

Launch 10+ MW_{AC}
GS Systems



Leverage Existing Industry Capabilities

EnerVault
Safe, Reliable, Cost-Effective Energy Storage

Established relationships supporting design, fabrication, controls, & deployment

NORAM Engineering

- Vancouver, BC
- Founded 1988, private, global project portfolio

Ascension Industries

- Buffalo, NY area
- Founded 1956, private, global project portfolio

Raytheon Ktech

DNV·GL
BEW Engineering (CA)

Sandia National Laboratories

System Scaling

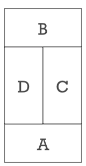
EnerVault
Safe, Reliable, Cost-Effective Energy Storage

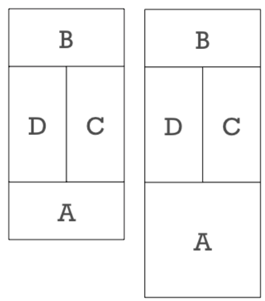
2014 | **2015** | **2016**

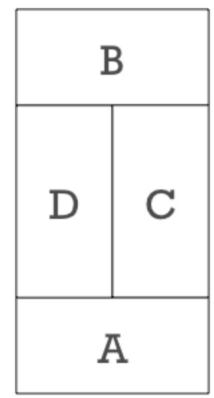
250 kW_{AC}/1 MW-hr Field System

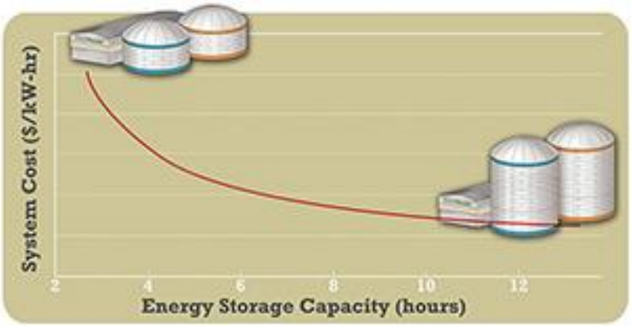
1-2 MW_{AC} IS Systems

10+ MW_{AC} GS Systems









Modular Power:
tunable, higher availability

Aggregated Energy:
lower cost, better operability, lower maintenance

THANK YOU

EnerVault
Safe, Reliable, Cost-Effective Energy Storage

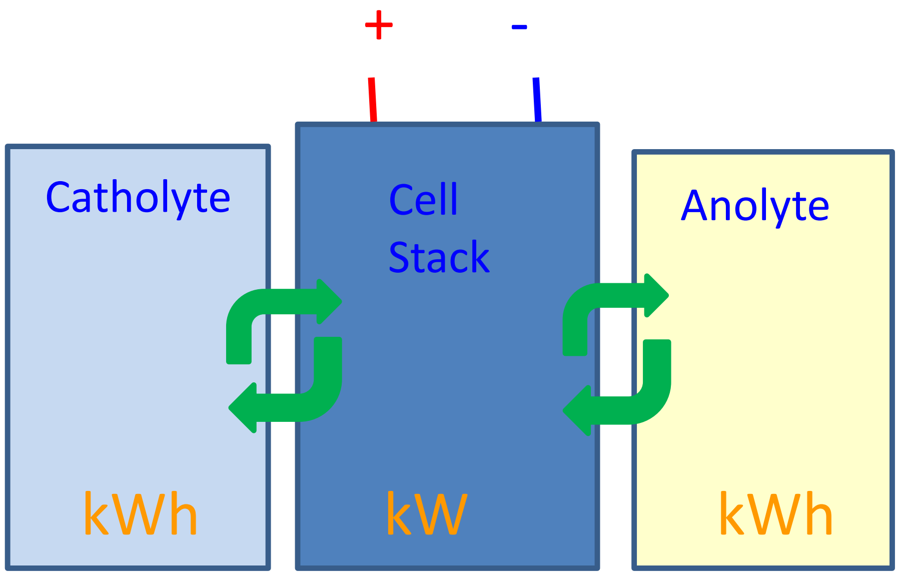
Uni.System™: Advanced Vanadium Flow Battery System for Grid Applications

June 19, 2014

Flow Battery Basics, Part 1:

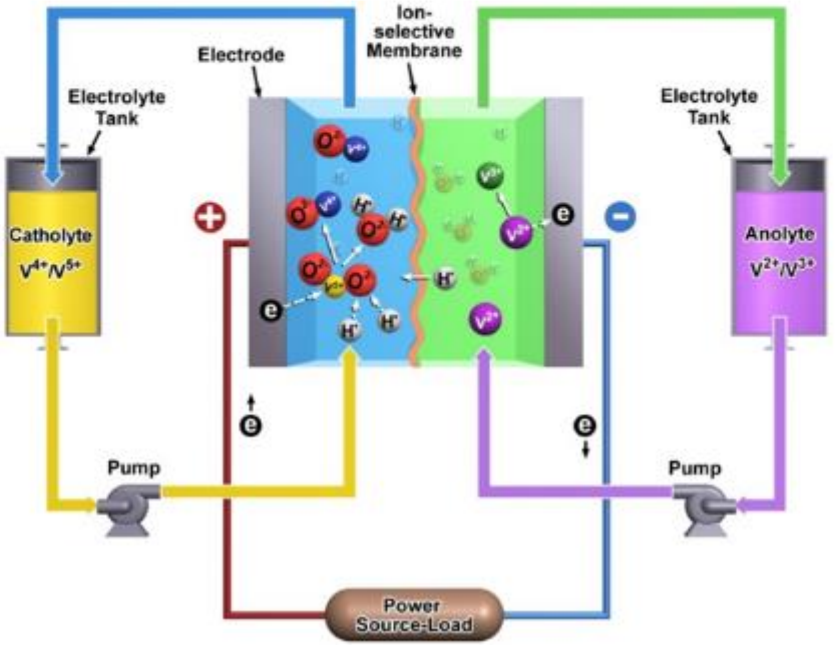
What They Are, How They Work, Where They're Used

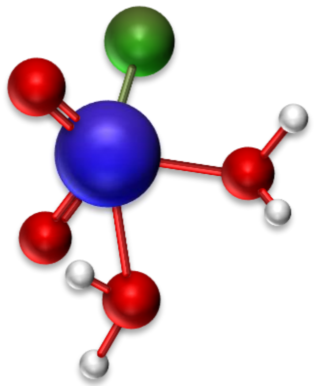
About Flow Batteries



- Separation of
  - Energy (kWh) – electrolytes
  - Power (kW) – cell stacks
- "Inert" electrodes – no stress buildup or structural degradation in electrodes
  - Extended electrode durability/reliability
  - Long cycle life, independent of SOC/DOD
- Effectively stop reactions by turning pumps off – no thermal runaway – **safe**
- Stores up to MWh's/MW's of electricity, with durations from mins up to hrs and even days – grid scale solutions
- Passive heat management – flowing electrolytes carry away heat generated; large volumes of electrolytes act as heat sinks -high reliability & efficiency

UET's Core Technology: Stable and Powerful Vanadium Chemistry





$VO_2Cl(H_2O)_2$

Cathode: $VO_2Cl + 2H^+ + e^- \leftrightarrow VO^{2+} + Cl^- + H_2O$

Anode: $V^{2+} - e^- \leftrightarrow V^{3+}$

Cell: $VO_2Cl + V^{2+} + 2H^+ \leftrightarrow VO^{2+} + V^{3+} + Cl^- + H_2O$

Pacific Northwest NATIONAL LABORATORY

New molecule designed with PNNL's super-computing and advanced analysis equipment

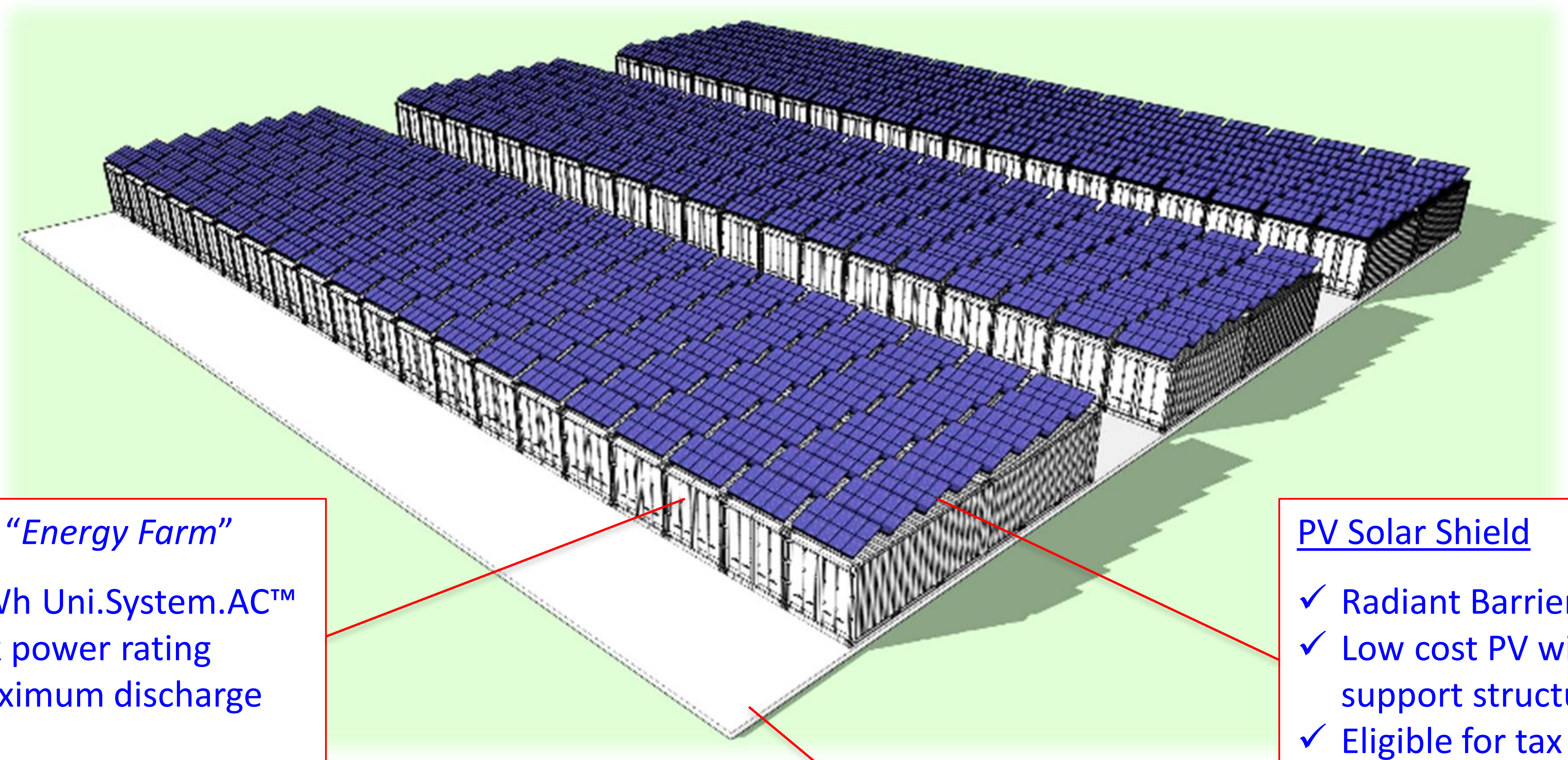
- Team of 20 scientists led by Dr. Gary Yang & Dr. Liyu Li who then founded UET in 2012
- Won the US Government' highest Award of Excellence in Technology Transfer to UET
- Extraordinary electrolyte stability
  - stable from **-40 °C to +50°C**
- 2X energy density improvement
  - → **5X footprint reduction**
- Inherent Safety
  - Non flammable
  - No thermal runaway
  - Reduced chemical volume
  - Nonreactive with water

\+ Containerization

2015 Uni.System.AC™: 500kW/4h; 600kW$_{peak}$; 2.2MWh$_{max}$

- ✓ Inherently Safe
  - *Water based, No thermal runaway*
- ✓ Robust and Reliable
  - *20 year life, No degradation*
- ✓ Operationally Flexible
  - *100% capacity access, Stack values*
- ✓ Scalable Architecture
  - *System footprint 20MW/acre*
- ✓ Wide Temperature Range
  - *-40 °C to +50 °C*
- ✓ Factory Integration
  - *precision assembly & QC*
- ✓ Plug & Play
  - *rapid incremental deployment*
- ✓ 97% Availability
  - *no stripping or equalizing*
- ✓ 100% Recyclable
  - *disposal contract included*

Scalable: 10 MW 40MWh concept



Uni.System.AC™ *"Energy Farm"*

- ✓ 10MW/40MWh Uni.System.AC™
- ✓ 12MW_{AC} peak power rating
- ✓ 44MWh_{AC} maximum discharge capacity

Total PV+Storage Footprint

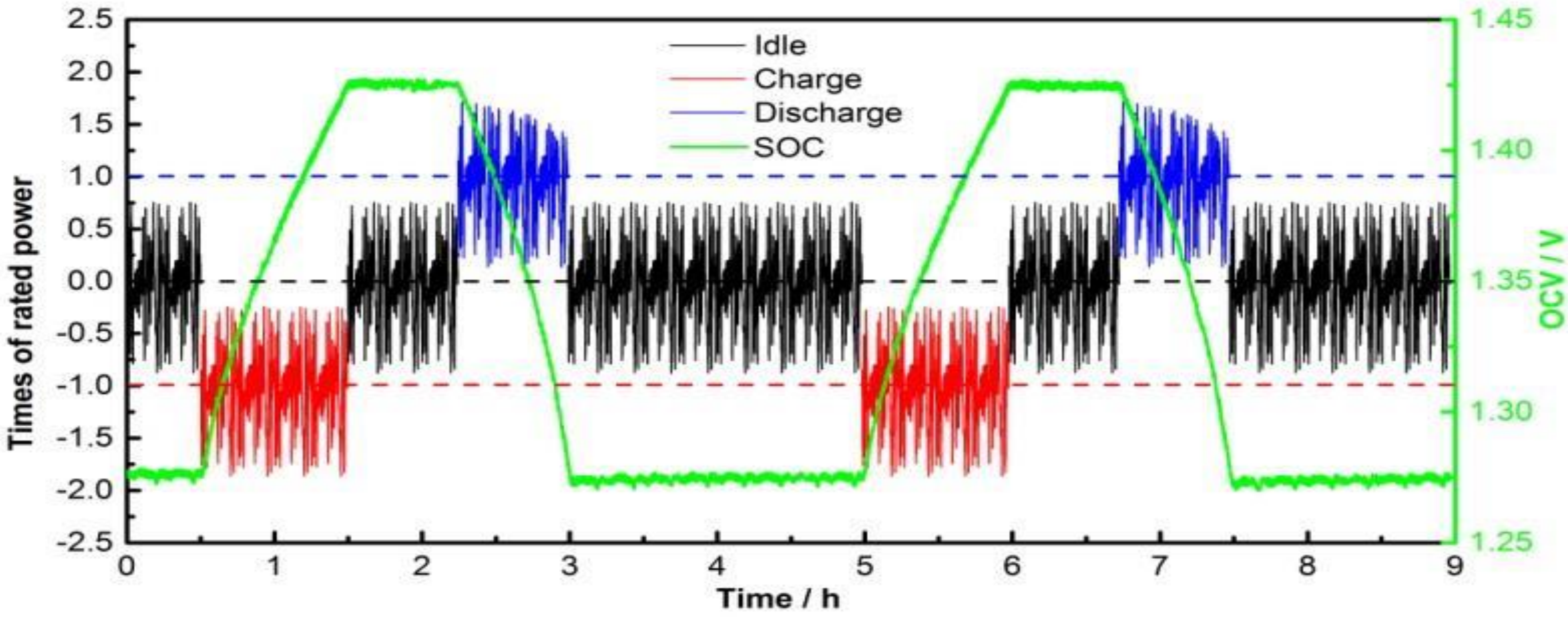
- ✓ 20MW/acre
- ✓ 8" thick concrete slab

PV Solar Shield

- ✓ Radiant Barrier for Energy Farm
- ✓ Low cost PV with Uni.System™ support structure
- ✓ Eligible for tax incentives
- ✓ 250kW array yielding 500MWh/y

Operationally Flexible

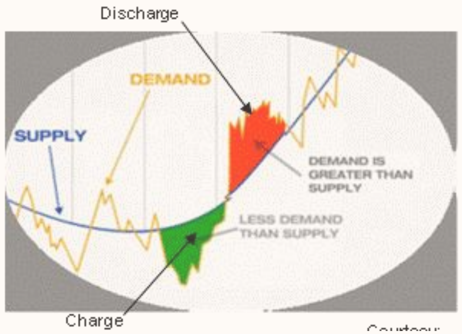
- The Uni.System™ is uniquely capable of performing short and long duration applications simultaneously

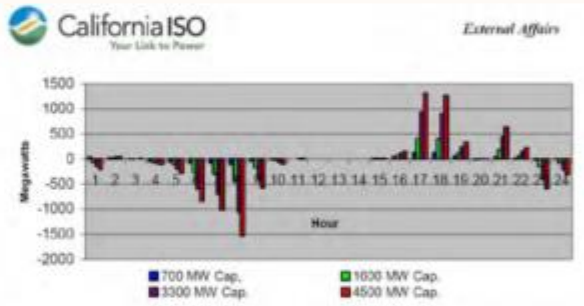


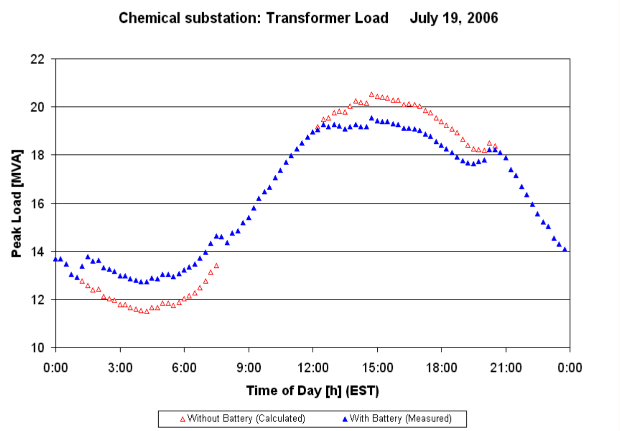
***Data from completed factory testing results*.**

Flexible, Operable Over Diverse Time Scales

Seconds to Minutes	Minutes - one Hour	Several Hours - one Day
Regulation	*Ramping, Firming*	*Peak shaving, load leveling*







Storage Applications Have Diverse Timefames and

Require

Flexible Storage Solutions

Flexible, Stacking to Deliver Cost Effective Solutions

	Use Case	Benefits	Traditional Solutions	Value Basis	Client Type
T-Connected Bulk Storage	Peaker, Resource	Resource Services, Capacity, Energy, A/S	CT	PPA, Mkt Rev, Avoided Cost	Developer, Utility
	T&D Capacity	Deliverability, Reliability, Resiliency	Line & Substation Expansion	Avoided Cost, NERC Compl., FTR revenue	Utility, Developer
Distribution Energy Storage	Distributed Peaker	Resource Services, Resiliency, Microgrids	Circuit & Substation Expansion, CT, DG	PPA, Mkt Rev, Avoided Cost	Developer, Integrator, Utility
	Substation & Circuit Sited Storage	Resource Services, Wires Capacity, Resiliency, Microgrids	Circuit and Substation Expansion, DG	Mkt Rev, Avoided Cost, SAIFI/SAIDI	Utility
	Renewble Mitigation and Integration	Ramp Mngt, Curtailment Reduction, Diesel Reduction	none	PPA, Avoided Cost Savings	Developer, Integrator, Utility
Behind-the-Meter Energy Storage	Behind the Meter	Bill Reduction, PQ	DR, DG	Bill Savings	Util Cust, Developer, Integrator
	Behind the Meter Utility Controlled	Bill Reduction, Avoid Cost, Market $, Grid Rel	Circuit Upgrade, DR, DG	Bill Savings, Avoided Cost	Utility Developer, Integrator

Comparison of 100MW Gas Turbine with 100MW Battery *

Energy storage can provide much greater benefits per MW as a flexible resource!

vs.

100 MW Gas Turbine
10 minute ramp
50 MW flexible range
2768 useable hours/year(1)
6500 gallons per hour
Status quo GHG emissions

output range 50 to 100MW

20-40% utilization

Energy Storage Benefits
>600x the ramp rate
>4x the flexible range
>3x the operational hours
Less water usage
Lower GHG emissions
Investment lowers costs

100 MW Energy Storage
<1 second ramp
200 MW of flexible range
>8300 useable hours/year
Little to no water usage
Reduces GHG emissions by up to 90%(2)

output range -100 to +100MW

95% availability

(1)Excluding start-up and shutdown time

(2)http://www.energy.ca.gov/2011_energypolicy/documents/2011-02-15_workshop/comments/California_Energy_Storage_Alliance_03032011_TN-59863.pdf

12 ENERGY STORAGE NORTH AMERICA 2013

* Summary slide from STRATEGEN at ESNA conference in September, 2013

Backup Slides

2015 Uni.System.AC™ Performance Data

	2015 Uni.System.AC™		
Peak Power	600 kW_{AC}		
Maximum Energy	2.2 MWh_{AC}		
Discharge time	2 h	4 h	8 h
Power	600 kW_{AC}	500 kW_{AC}	275 kW_{AC}
AC Efficiency	65-70%		
Voltage	12.47kV +/- 10%		
Current THD (IEEE 519)	<5%THD		
Response Time	<100ms		
Reactive Power	+/- 450kVAR		
Humidity	95%RH noncondensing		
Footprint	820 ft^2		
Envelope	41'W x 20'D x 9.5'H		
Total Weight	170,000 kg		
Cycle and Design Life	Unlimited cycles over the 20 year life		
Ambient Temp.	-40°C to 50°C (-40°F to 122°F)		
Self Discharge	Max capacity loss: <2%		

UniEnergy Technologies (UET)

Vision: Become a major global provider of bulk energy storage solutions through ***innovation, quality and strategic partnerships***

We are accomplishing this by commercializing a break-through redox flow battery product with new generation high performance electrolytes, field-proven stacks, optimized control/power electronics, and refined "plug & play" containerization

Achievement: UET has successfully developed and deployed the world's first flow battery product fully integrated into a single shipping container for rapid and flexible grid deployment

UET Capabilities

- State-of-the-art R&D lab and world class scientists
- Leading engineering team with decades of experience in flow battery and related industries
- Precision assembly & QC, ramping up production to 100MW per year in the next 2~3 years
- Seasoned sales & marketing team

UET's DNA and Strategic Partnerships

NEW ELECTROLYTE

- ✓ 2X power and energy density
- ✓ –40°C to +50°C
- ✓ Improved safety

Pacific Northwest
NATIONAL LABORATORY

DOE

PRODUCT ENGINEERING AND MANUFACTURING

67,000ft^2 design, development & manufacturing facility in Seattle

FIELD EXPERIENCE

- ✓ 5MW/10MWh wind firming installation
- ✓ Numerous MW-class microgrid sites

RONGKE POWER

ELECTROLYTE PRODUCTION

- ✓ 1,324,000 ft^2 production facilities
- ✓ Electrolyte production capacity > 1.5GWh/year
- ✓ ISO9001:2008 Certified

STACK PRODUCTION

- ✓ 108,000 ft^2 manufacturing facility
- ✓ 100MW production capacity
- ✓ ISO9000/14000, GB/T28001 Certified

Thank You

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ESTAP Website: http://www.cesa.org/projects/energy-storage-technology-advancement-partnership/

ESTAP Listserv: http://www.cesa.org/projects/energy-storage-technology-advancement-partnership/energy-storage-listserv-signup/

Clean Energy States Alliance

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY