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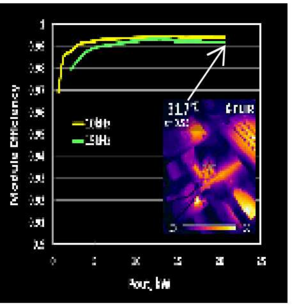

Energy Storage & Power Electronics

Stan Atcitty

Energy Storage Technology and Systems Department 08811

Sandia National Laboratories

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Energy Storage Is Critical to the Stability and Resilience of the Electric Grid

Traditional Grid

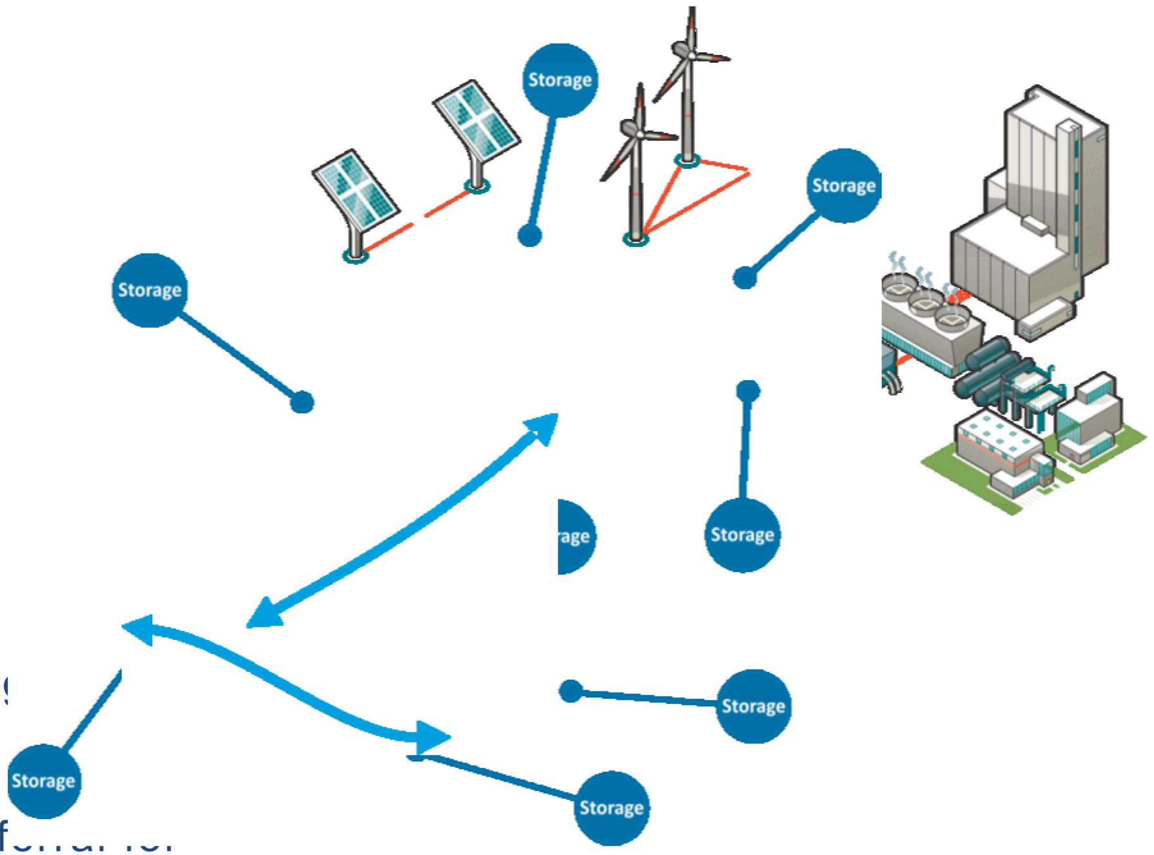
- One way flow
- Little/no renewable ener

Today's Grid

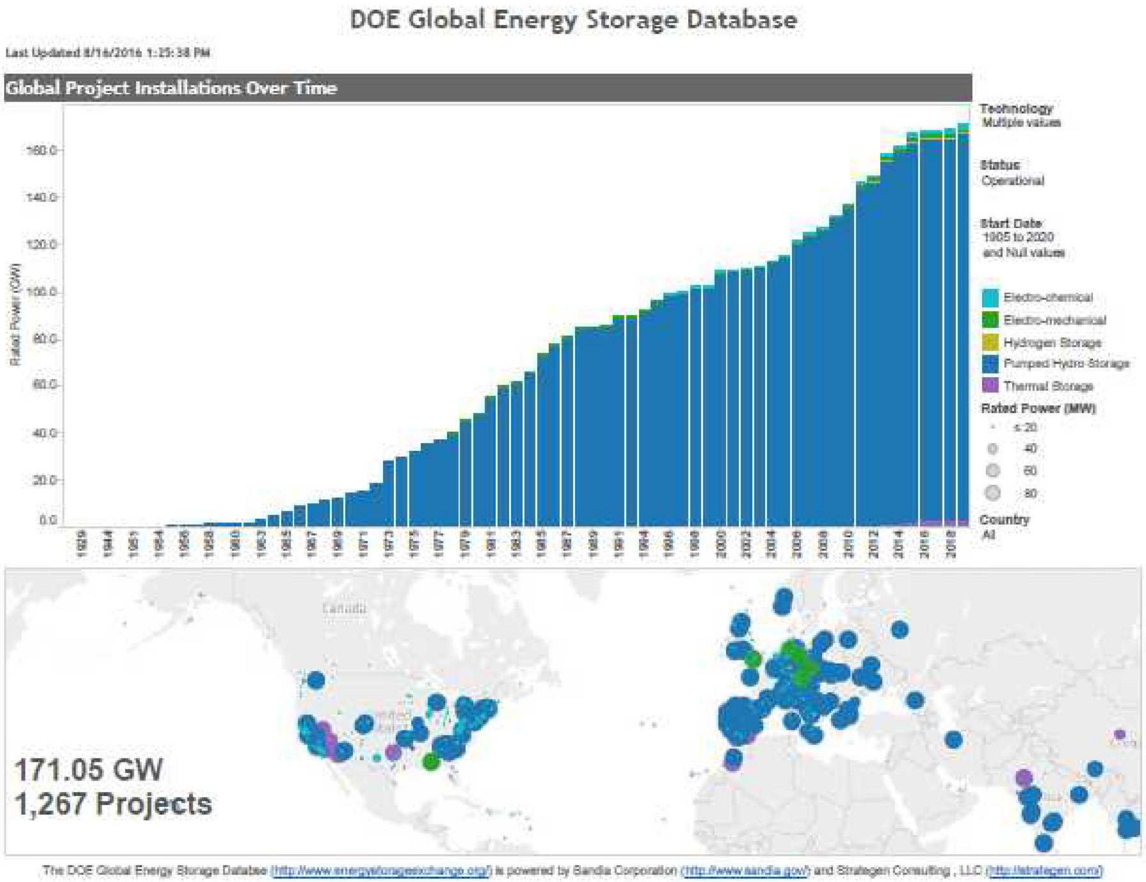
- Integration of grid-scale and distributed renewable generation beginning, but with limited penetration

Future Grid

- Storage provides bufferin capability to enable high penetration of variable renewables and asset def... T&D systems (load management, ancillary services)
- Efficient two-way flow



DOE Global Energy Storage Database



DOE Energy Storage Database
www.energystorageexchange.org

DOE Database (since 2012)

- Over 1,200 Projects, 21 Policies
- Users in over 189 countries
- 50+ Energy Storage Technologies
- Data Visualization Tools

According to market research firm IHS, the energy storage market is set to grow to an annual installation size over 40 GW by 2022.

Elements of Energy Storage System

Storage

- Cell
- Battery Management & Protection
- Racking

Integration

- Container / Housing
- Wiring
- Climate control

PCS

- Bi-directional Inverter
- Switchgear
- Transformer
- Skid

EMS

- Charge / Discharge
- Load Management
- Ramp rate control
- Grid Stability

Energy Storage at Sandia

Energy Storage is a major Crosscut at the lab.
Wide ranging R&D covering energy storage technologies with applications in the grid, transportation, and stationary storage

Major R&D Thrust Areas

- Materials and Systems Development
  - Development of next-generation technologies
  - Improving current technology (flow batteries, flywheels, membranes, etc.)
- Power Electronics
  - Development of power electronics and power conversion systems.
- Energy Storage Systems Safety and Reliability
  - Fundamental Safety R&D of utility class storage systems
  - Laboratory testing and analysis from individual cells to 1MW systems
- ES Systems Demonstrations and Testing
  - Field deployments; State-Initiated Demonstration Project Development
- Grid Analytics and Policy
  - Providing assessments of the impact of storage placement
- Outreach - publications and meetings to help educate the Grid Energy community
  - EESAT and DOE Energy Storage peer review
  - US DOE Global Energy Storage Database
- Microgrid design

Energy Storage Technologies

Energy

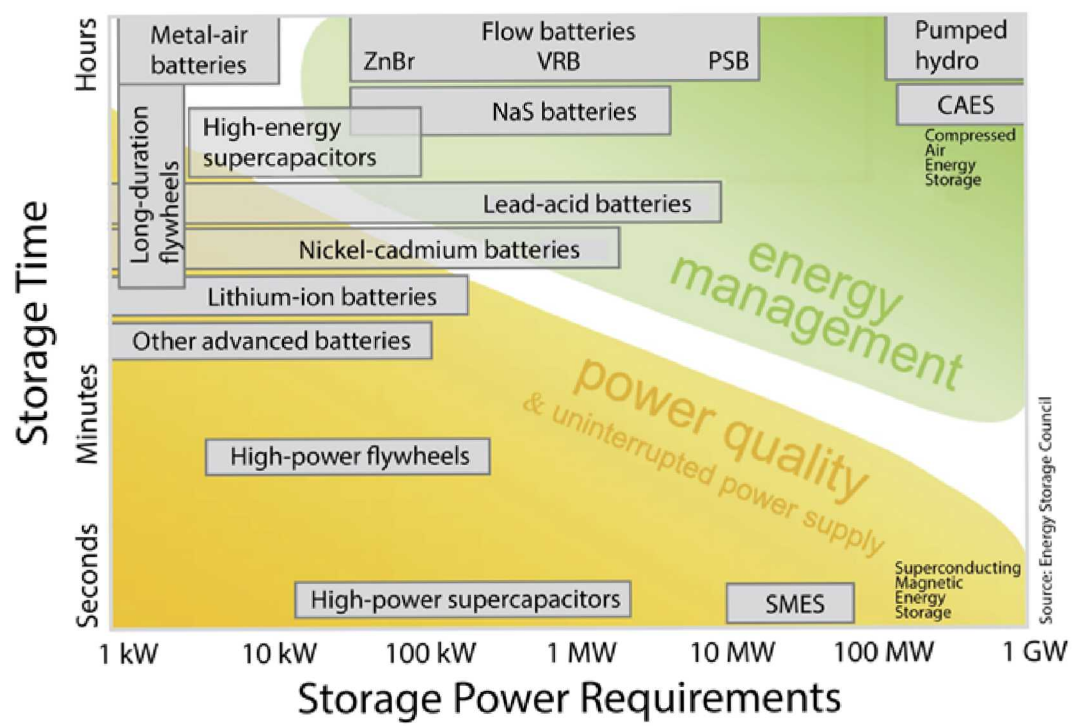
- Pumped Hydro
- Compressed Air Energy Storage (CAES)
- Batteries
  - Sodium Sulfur (NaS)
  - Flow Batteries
  - Lead Acid
  - Advanced Lead Carbon
  - Lithium Ion
- Flywheels
- Superconducting magnetic energy storage (SMES)
- Electrochemical Capacitors

Power

Two regimes, multiple technologies:

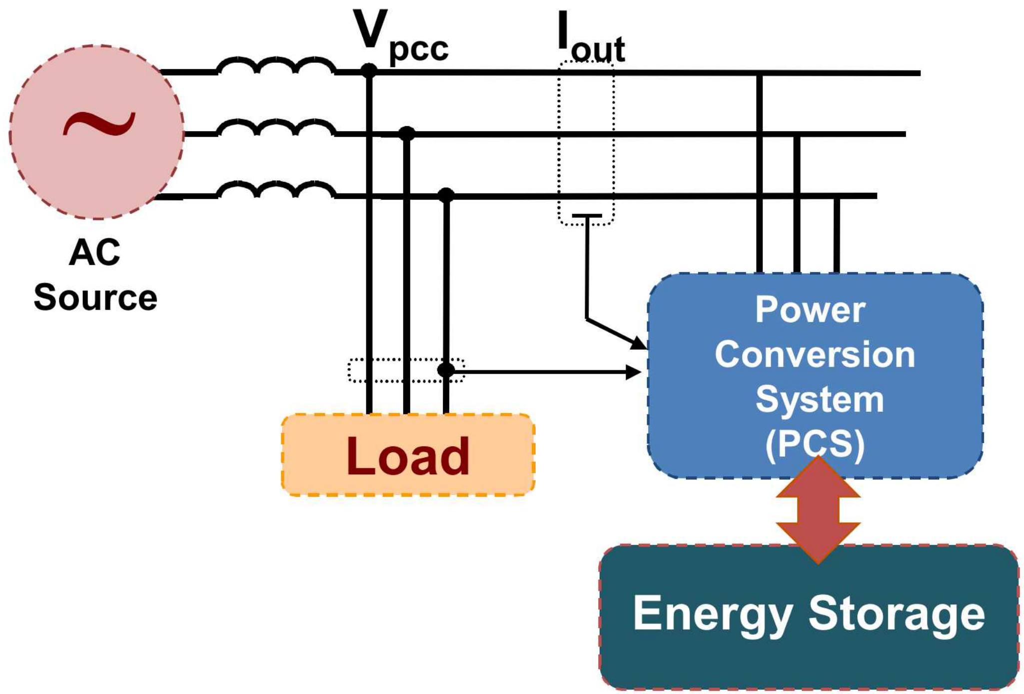
Power – short discharges (sec to min):
flywheels, capacitors, SMES, some batteries

Energy – long discharges (min to hr):
batteries, H_2 fuel cells, CAES, pumped hydro



Why is DOE OE/Sandia interested in power electronics?

- Needs:
  - Reduce install cost/kW
  - Decrease size and weight especially for transportable systems
  - Improve integration control
  - Increase reliability
  - Increase efficiency

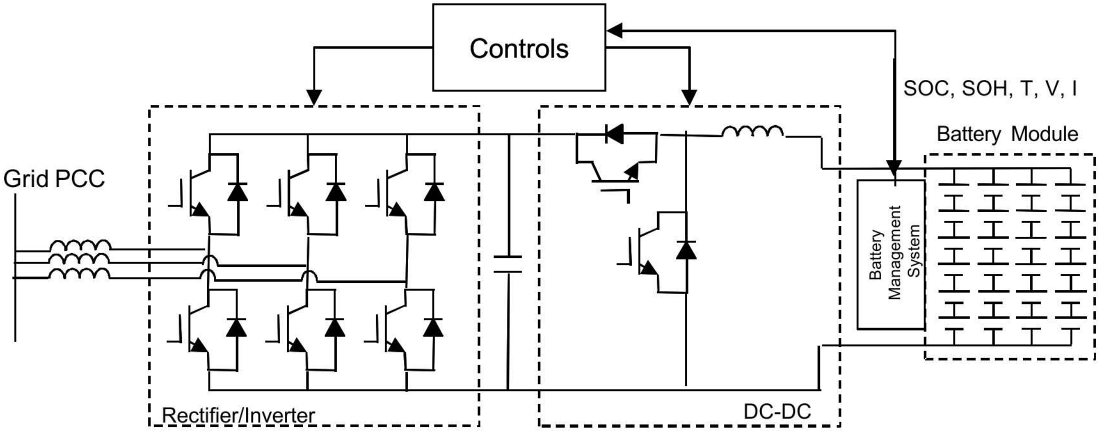


The PCS is a key component of the energy storage system. It can represent 20 to 60% of the total system cost.

Battery Energy Storage System

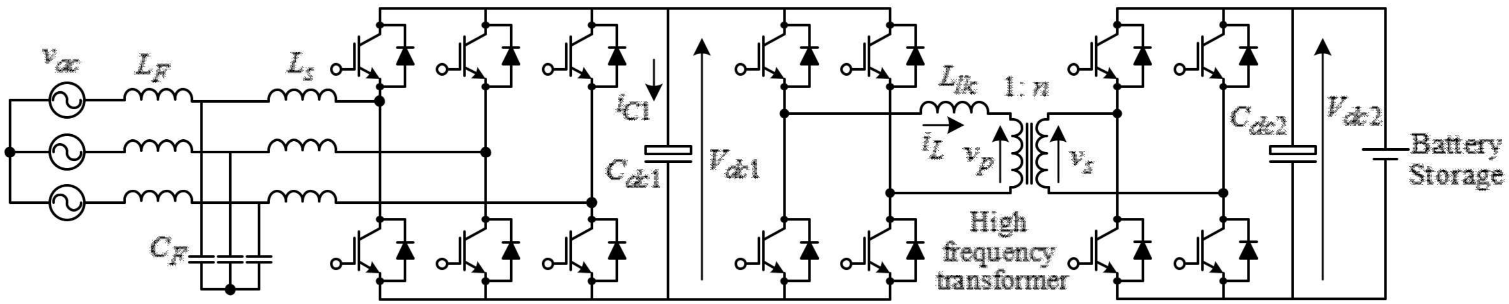
- Background
  - Electrochemical energy storage device
  - Consist of one or more cells, main components include cathode (+)/anode (-) terminals, electrolytes, and separator. Converts chemical energy to electrical energy.
  - Pb-acid, Li-ion, NaS, Metal Air, Advanced Pb C, etc.
  - Key design objectives – high cell voltage, high energy or power formats, safe systems, and high reliability
- Benefits
  - Applications – wide spectrum from PQ to peak shaving
  - Power & energy range, few kWs to 10s MW
- Challenges
  - Power conversion system, batteries, grid interconnect
  - Reliability, safety, round trip efficiencies

18650 Cell



Typical Electrical Configuration of a BESS

High Switching Frequency Benefits

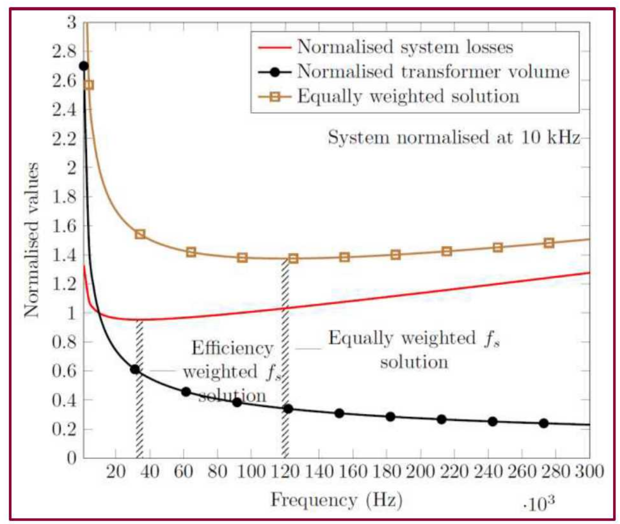


100 kHz Ferrite Transformer
8 kW – 328 grams (0.72 lbs)

60 Hz Si-Steel Transformer
7.5 kVA – 150 lbs

Source: Wolfspeed

High frequency γ'-Fe_4N core can meet all requirements of high frequency power electronics

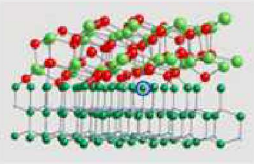


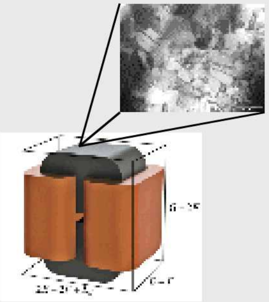
Source: S. Kulasekaran, R. Ayyanar, S. Atcitty, *Switching frequency optimization of a high-frequency link based energy storage system*, IECON 2014-40th Annual Conference of the IEEE IES, Oct 29 -Nov 1, 2014, pp. 1847-1853

Energy Storage Power Electronics Program

Materials R&D	Devices	Power Modules	Power Conversion System	Applications

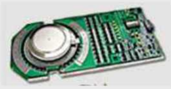
Materials R&D

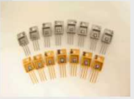




- Gate Oxide R&D
- Advanced Magnetics

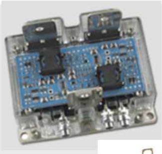
Devices

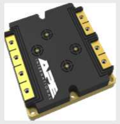




- ETO
- SiC Thyristors
- Monolithically integrated SiC transistors
- WBG Characterization & Reliability
- High energy dielectric capacitors

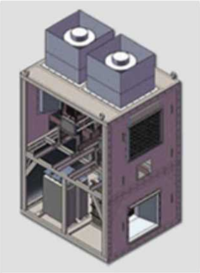
Power Modules





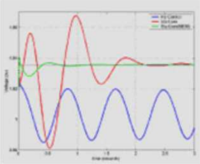
- SiC High Temp/density Power Module
- HV SiC JFET Module
- HV, HT Reworkable SiC half-bridge modules

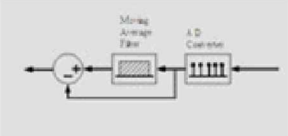
Power Conversion System

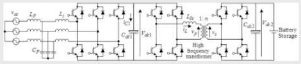


- Dstatcom plus energy storage for wind energy
- Optically isolated MW Inverter
- High density inverter with integrated thermal management
- High temp power inverter

Applications







- FACTS and Energy Storage
- Power smoothing and control for renewables
- Dual active bridge for advanced energy storage system designs

Contact

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Concentrating Solar Power and Thermal Energy Storage

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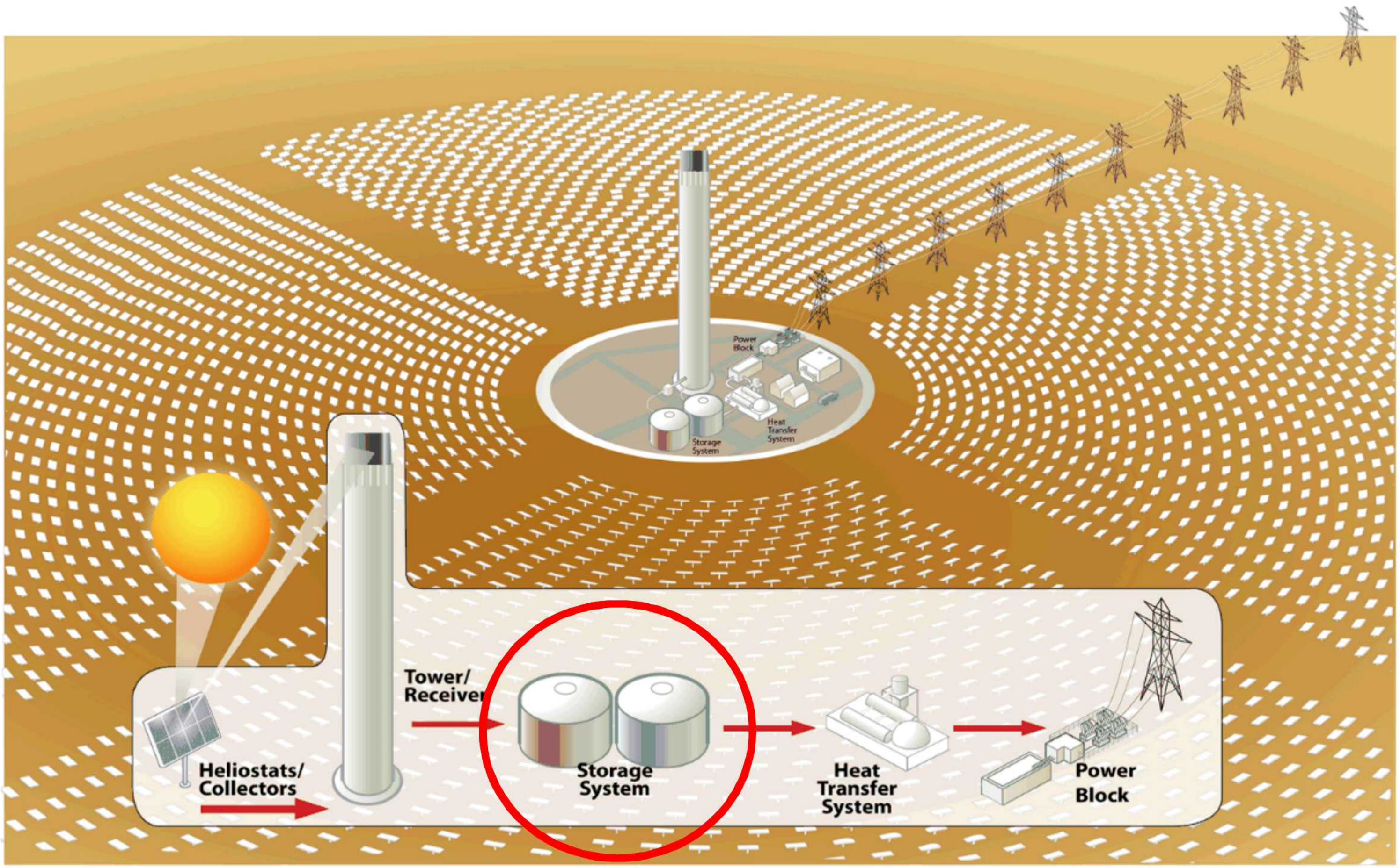
SAND2016-8168 PE

CSP and Thermal Energy Storage

- **Hot fluid can be stored as thermal energy efficiently and inexpensively** for on-demand electricity production when the sun is not shining



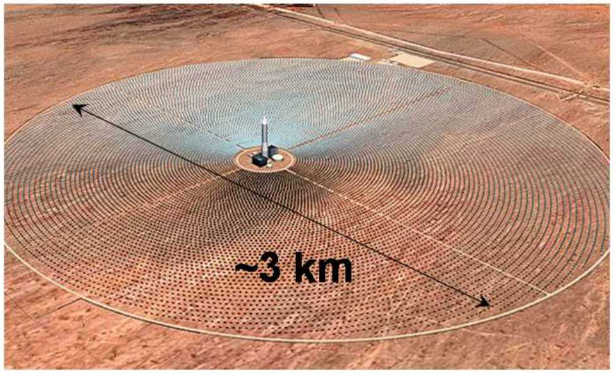
Gemasolar

(near Seville, Spain)

- 1st commercial power tower (19 MW) in the world with 24/7 dispatchable energy production (15 hours of thermal storage using molten salt). Commissioned in May 2011.

Crescent Dunes

Tonopah, Nevada



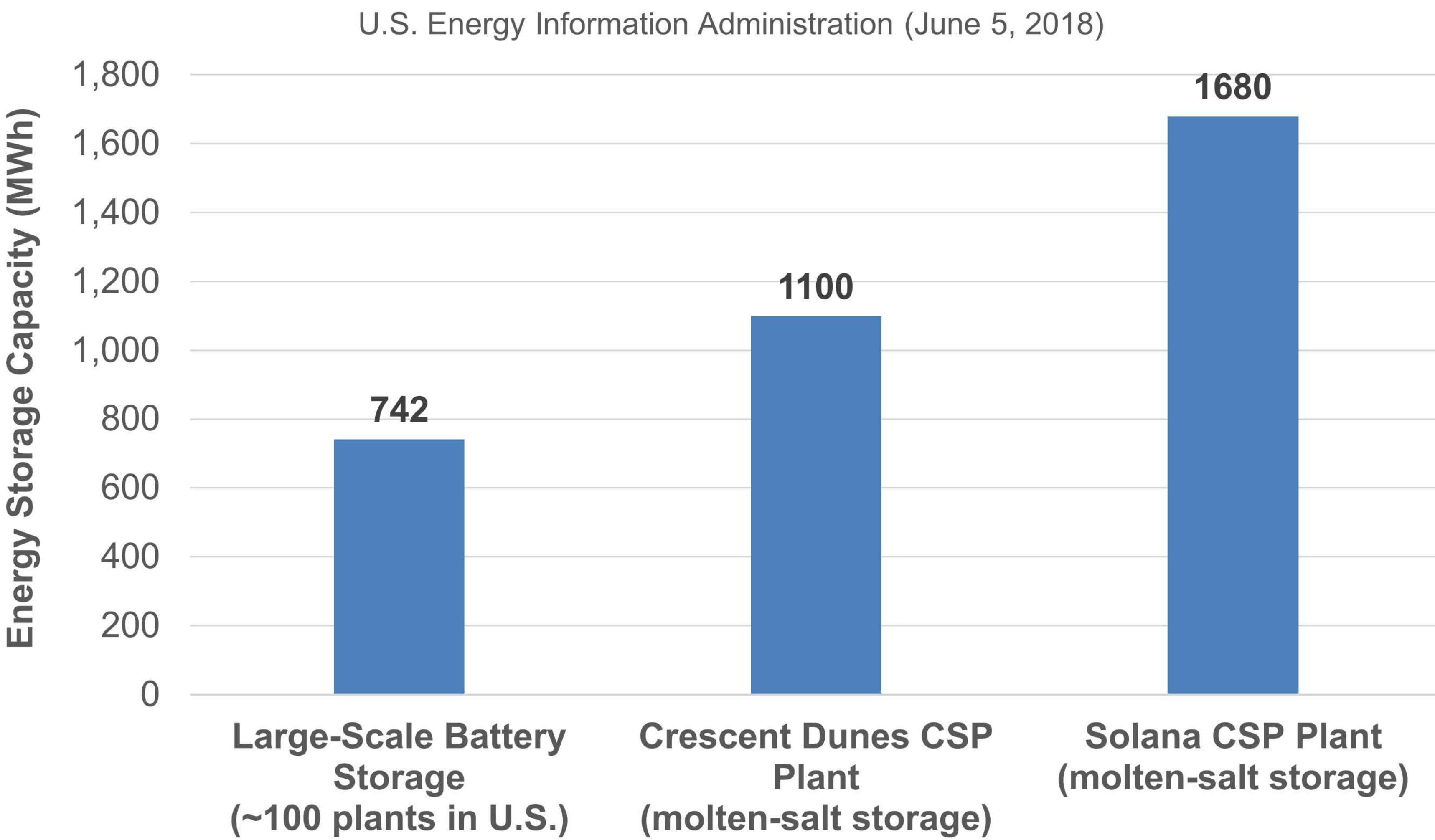
110 MWe molten-salt power tower with 10 hours of storage near Tonopah, NV. Construction from 2011 – 2015 (SolarReserve)

Solana Generating Station

280 MW parabolic trough plant
Phoenix, AZ (Gila Bend)
Started 2013

6 hours of molten-salt storage

Comparison of Large-Scale Battery and Thermal Energy Storage Capacity in the U.S.



Summary

- Concentrating solar power and thermal energy storage provides large-scale, long-term energy storage option
- Thermal energy storage options
  - Sensible heat storage (molten salt, particles)
  - Latent heat storage
  - Thermochemical storage
- Cost of CSP with storage is currently cheaper than photovoltaics with large-scale battery storage

Thank you!

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BACK UP SLIDES

Types of Thermal Energy Storage

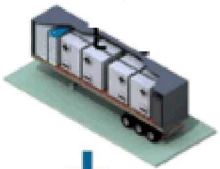
- Sensible (single-phase) storage
  - Use temperature difference to store heat
  - Molten salts (nitrates, carbonates, chlorides)
  - Solids storage (ceramic, graphite, concrete)
- Phase-change materials
  - Use latent heat to store energy (e.g., molten salts, metallic alloys)
- Thermochemical storage
  - Converting solar energy into chemical bonds (e.g., decomposition/synthesis, redox reactions)

Molten-salt storage tanks at Solana CSP plant in Arizona. Credit: Abengoa

Cost Structure of Storage System in 2016

Storage
Racks+BMS

+

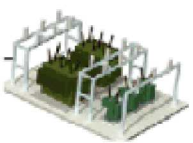


Product
Integration

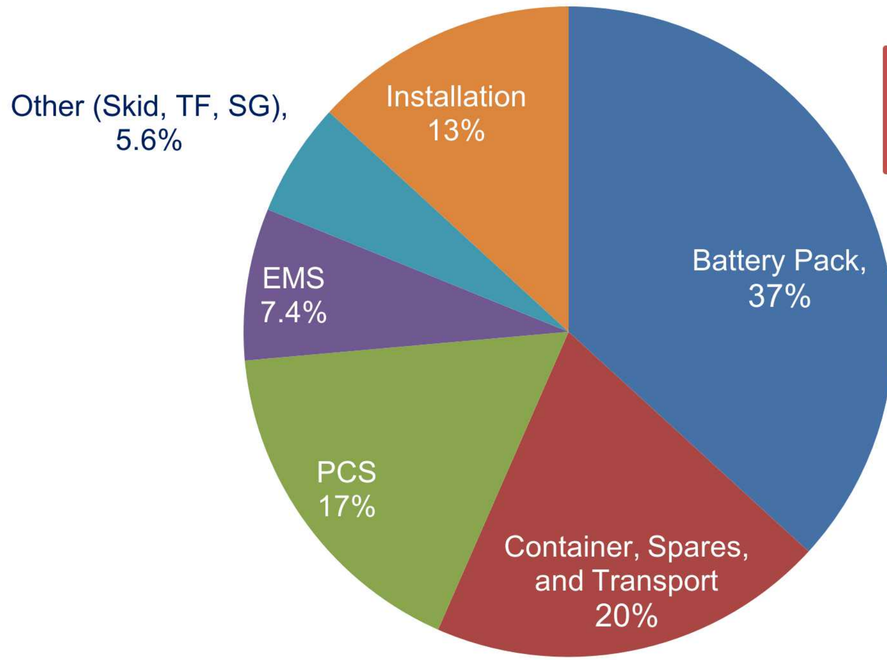
+

Power
Conditioning
(PCS)

+



Field EPC
Grid Integration



1MW/1MWh
LIB ESS

Projected cost line items for a 1MW/1MWh Li-ion energy storage system ($600/kWh and above depending on the system configuration)

Almost 60% of storage system cost is outside the Battery Pack

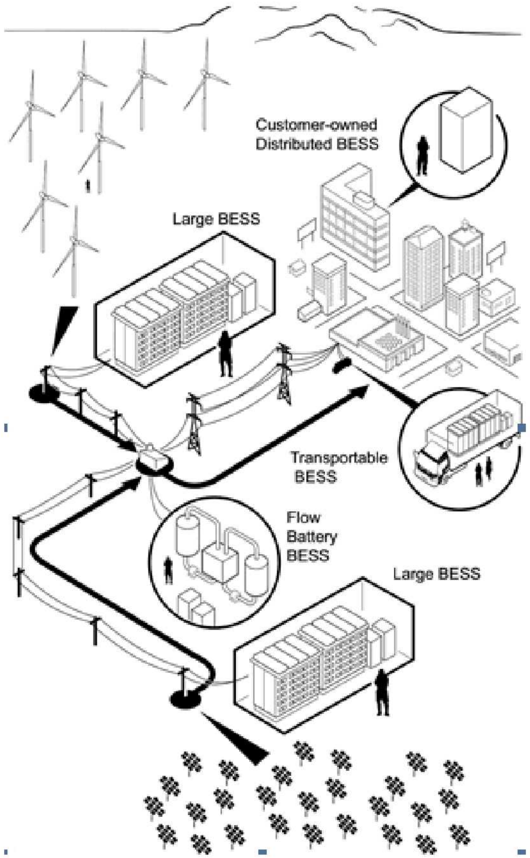
Data: Multiple industry sources

Making Energy Storage Cost Competitive

- Critical challenges for energy storage are high system cost and cycle life
  - Existing storage solutions are expensive
  - Deep discharge and longer cycle life
  - Safe and reliable chemistry
  - Scalable technology to cover all markets
- To make storage cost competitive, we need advances across all major areas:
  - Batteries, power electronics, PCS
  - BOS and Integration
  - Engineered safety of large systems
  - Codes and Standards
  - Optimal use of storage resources across the entire electricity infrastructure

Benefits of Electricity Storage

- Maintain quality power and reliability
- Provide customer services — cost control, flexibility, and convenience
- Improve T&D stability
- Enhance asset utilization and defer upgrades
- Increase the value of variable renewable generation

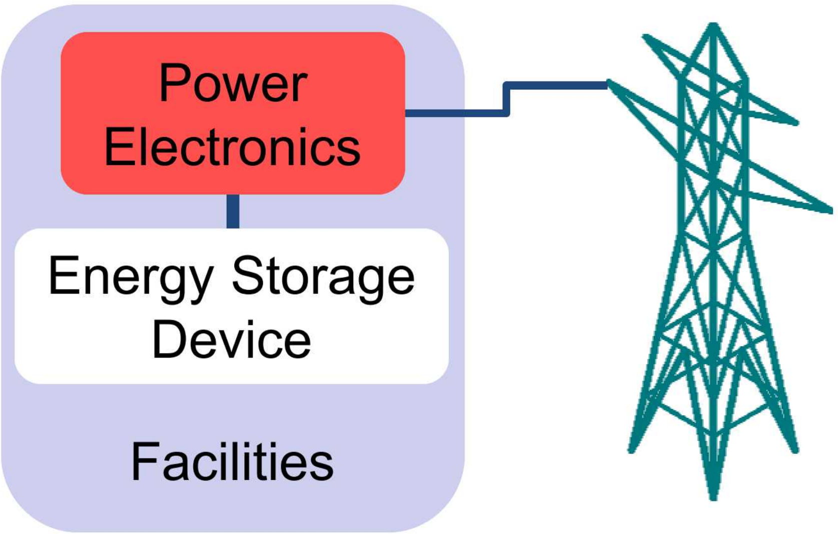


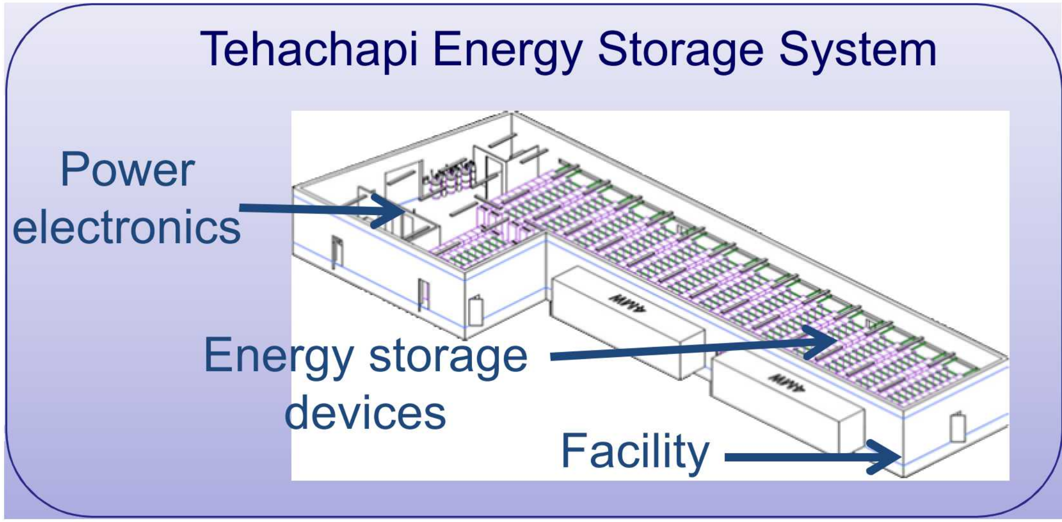
Source: Power Electronics for Renewable and Distributed Energy Systems: A Sourcebook of Topologies, Control and Integration

Energy Storage System Configuration

Energy Storage Systems contain three major components:

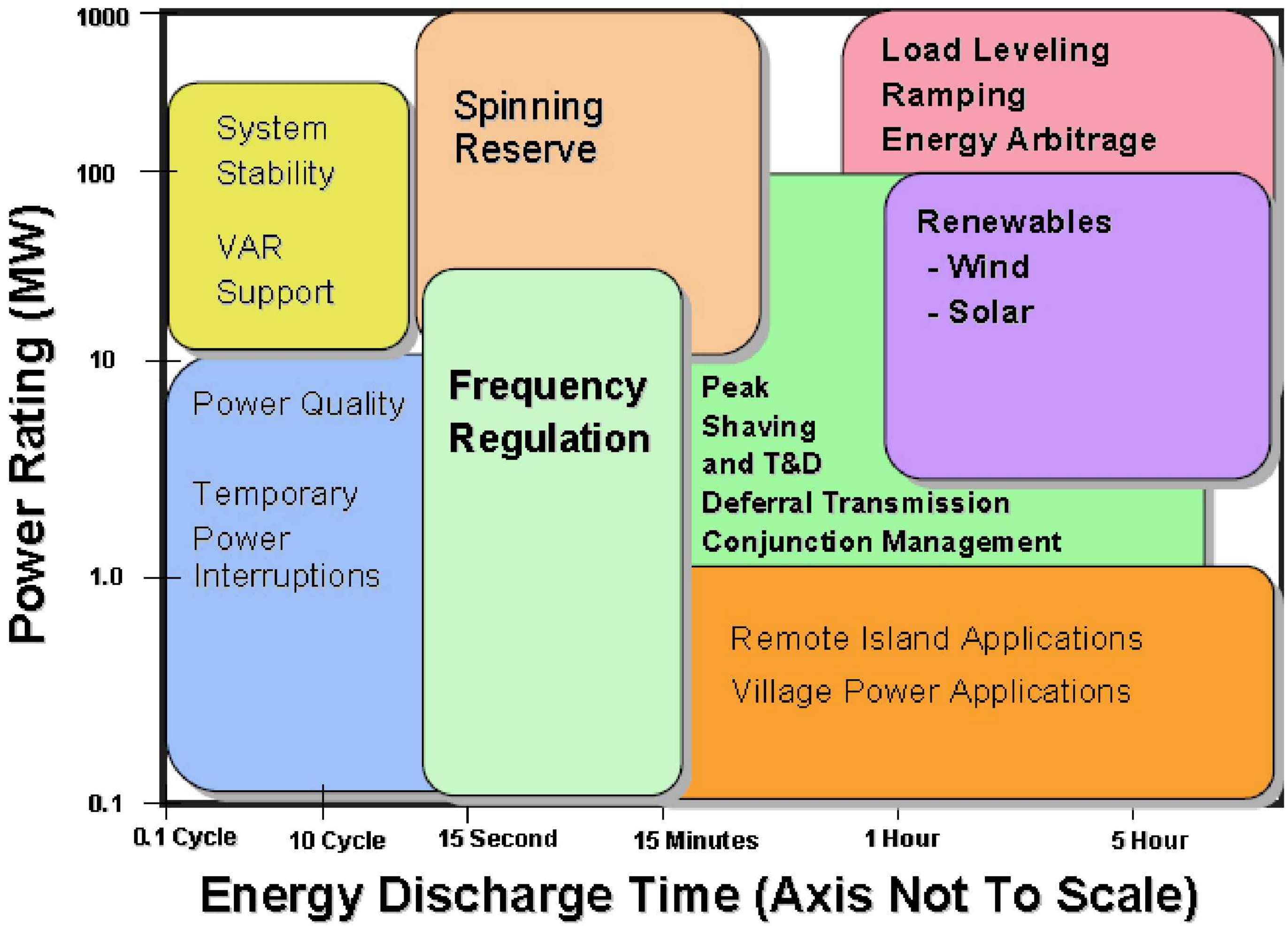
- Energy storage device
  - Where energy is held until needed
  - Ex: chemical/electrolyte (used in battery), flywheel, etc.
  - ~25-40% of overall costs
- Power electronics
  - Ensures proper and safe charge and discharge of storage device and can provide grid support
  - ~20-25% of overall costs
- Facilities (balance of plant)
  - Houses all equipment, protects system from physical damage
  - Can include HVAC
  - ~20-25% of system costs





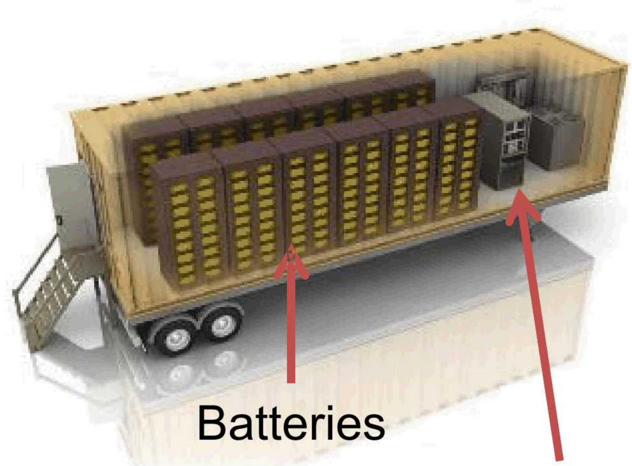
Other costs: consulting, financing, shipping, installation

Power and Energy



Source: Electric Power Research Institute

Transportable Energy Storage Systems



Benefits

- Lower Installation Cost
- Less Time from Installation to Operation
- Use at Multiple Sites Optimizes Overall System Use

Flywheel Energy Storage System

$$(E - m_{ratio})_{max} \sim wmax$$

$$E_k = \frac{1}{2} \cdot I \cdot \omega^2$$

$$I = \frac{1}{2} m({r_1}^2 + {r_2}^2)$$

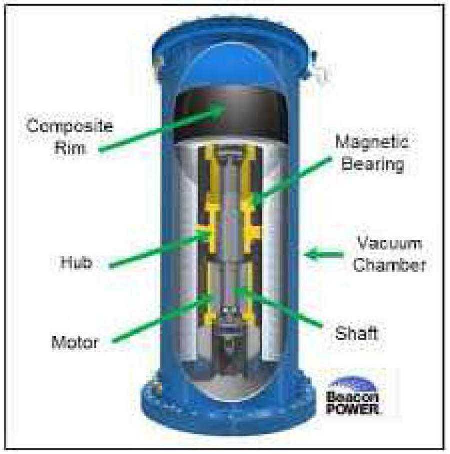
$\omega = angular\ velocity$

$I = moment\ of\ inertia$

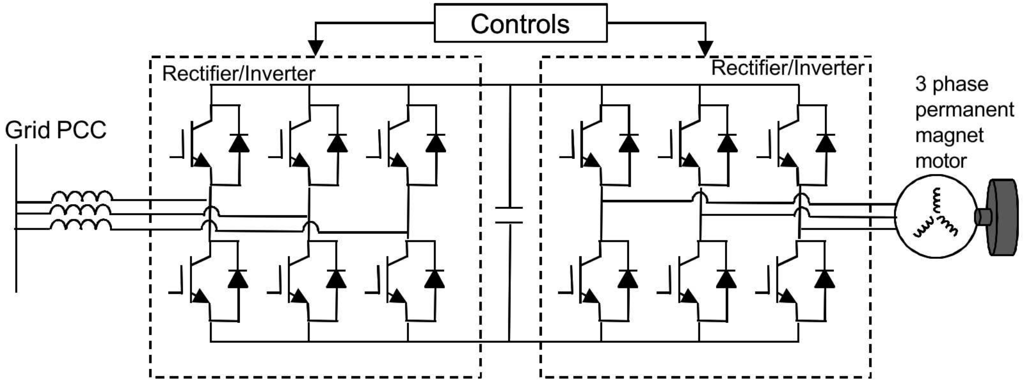
$m = mass$

$r = radius$

- Background
  - Kinetic energy storage device
  - Low speed FW, steel, up to 300-400 m/s tip speed
  - High speed FW, composite, 600-1000 m/s tip speed
- Benefits
  - High power, high cycle, low energy applications (i.e. Power quality, frequency regulation, transient stability, UPS)
  - Inherent long cycle life, >10^6 cycles
  - Energy range, < 1 kWh to 100s kWh
- Challenges
  - High frequency composite FW -> high BW power conversion system
  - Balance of system cost



Source: Beacon Power, LLC



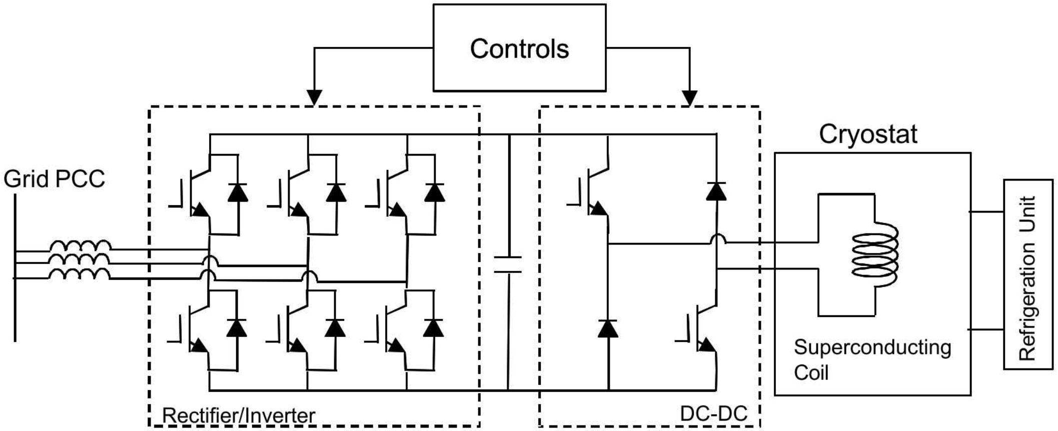
Typical Electrical Configuration of a FWES

Superconducting Magnetic Energy Storage System

$$E = \frac{1}{2} \cdot L \cdot I^2$$

- Background
  - Magnetic energy storage device
  - Energy stored in magnetic field generated by the current in the superconducting coil (i.e. R ~0 ohms). Energy released when coil is discharged.
  - Since R~0 ohms, charge and discharge is very quick
- Benefits
  - High power and cycling applications (Power quality, transient stability, frequency regulation, UPS)
  - Power range, 10s MW to 100s MW
- Challenges
  - Balance of system cost
  - Low energy density

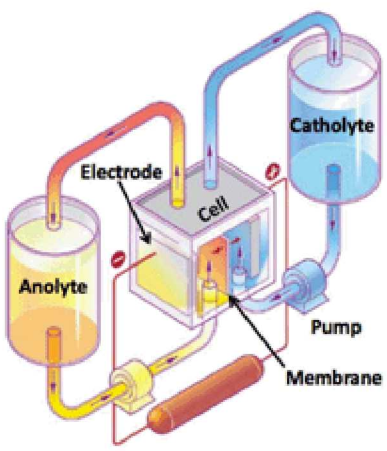
Source: T. Katagiri, H. Nakabayashi, T. Nijo, T. Tamada, T. Noda, N. Hirano, T. Nagata, S. Nagaya, M. Yamane, Y. Ishii, and T. Nitta, *Field Test Result of 10MVA/20MJ SMES for Load Fluctuation Compensation,* IEEE Transaction on applied Superconductivity, Vol. 19, No. 3, June 2009



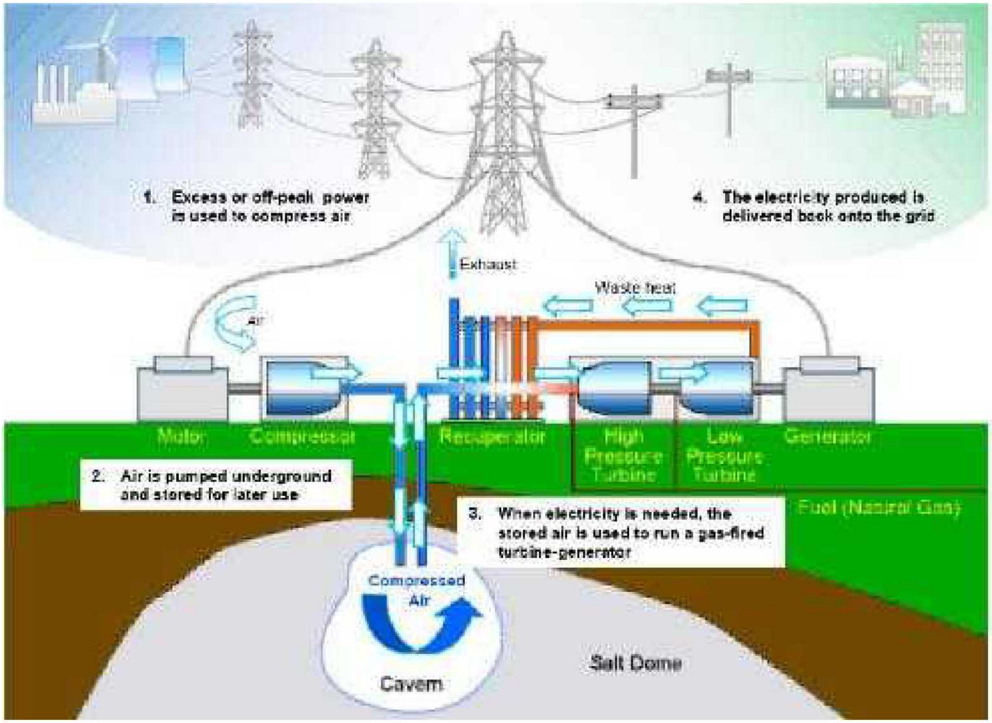
Typical Electrical Configuration of a SMES

Other Energy Storage Technologies

Electrochemical Capacitor Energy Storage



Flow Battery Energy Storage

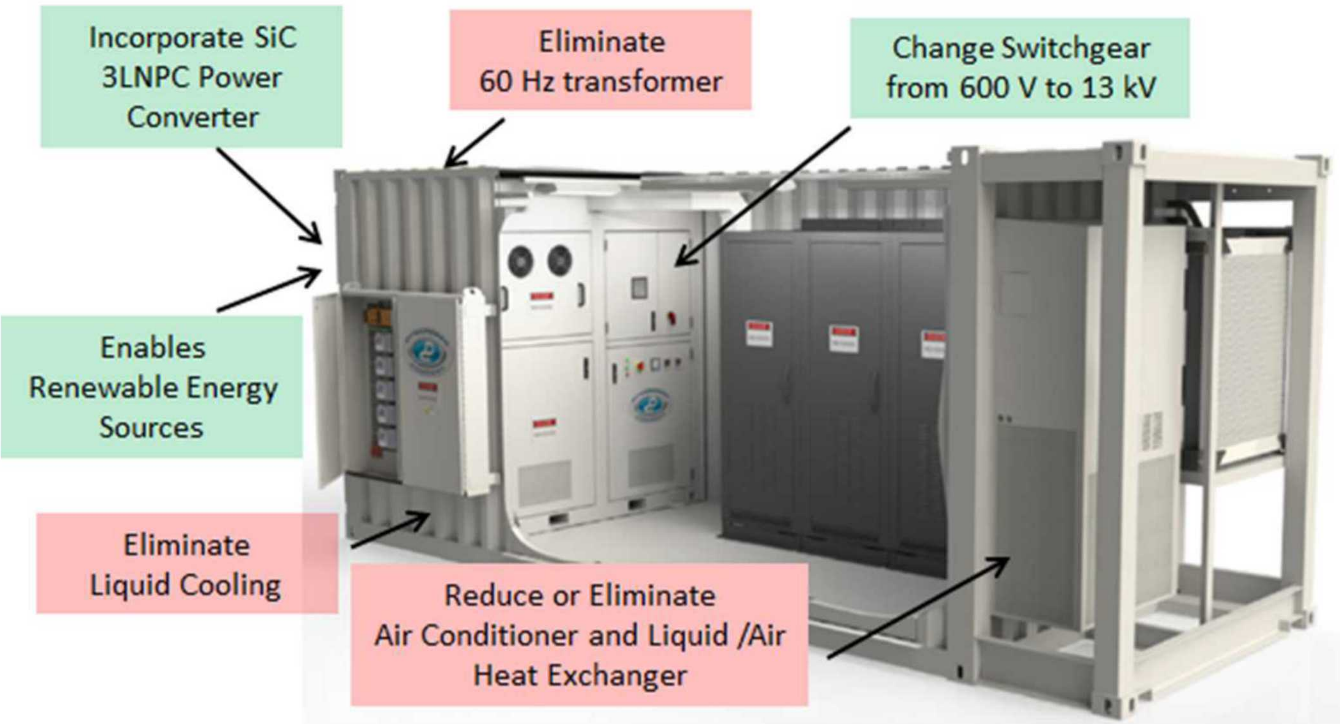


Compressed Air Energy Storage

Example: 500kW PCS using SiC

Existing 500 kVA Grid Tied Energy Storage Container (Dynapower)

Key: Eliminate Add

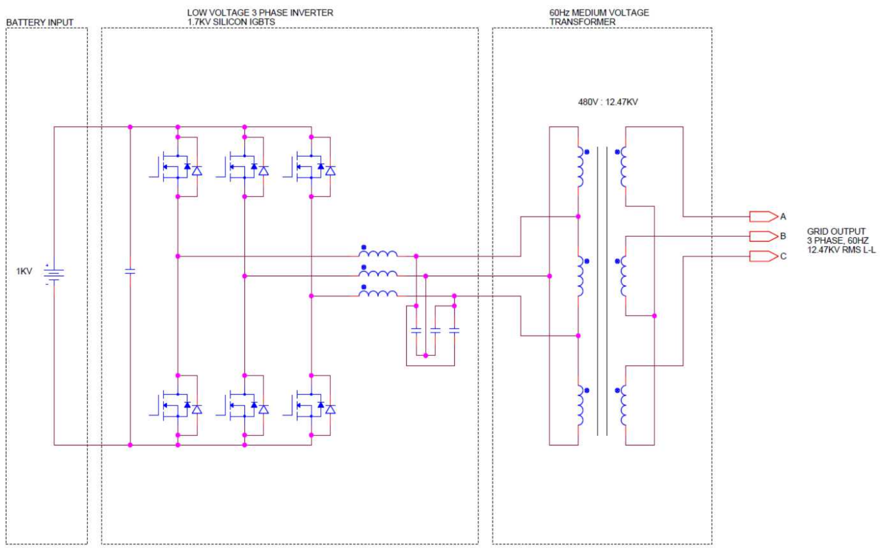


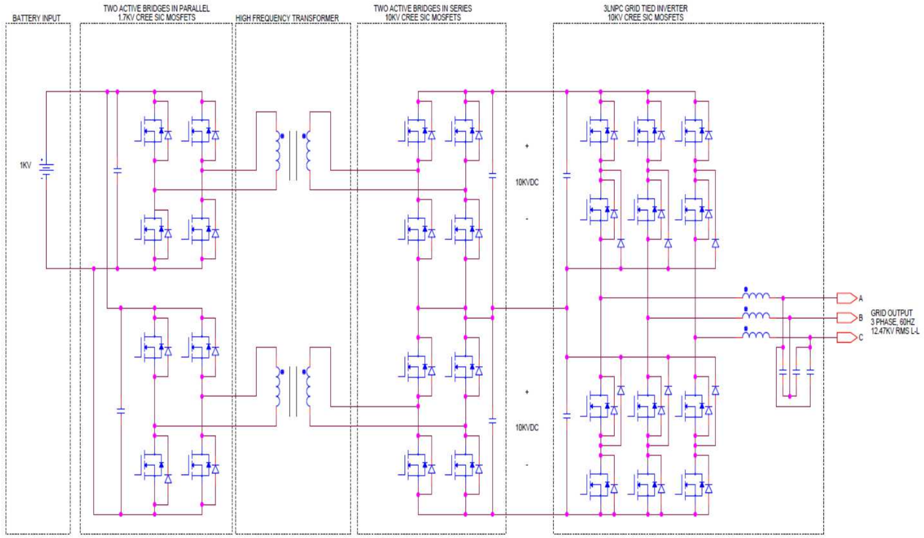
Nominal Existing Generation System

- 500 kW, 250 kW-hr
- 23 x 8 x 10 ft.
- Includes AC & DC switchgear
- Optional: solar recombiner (600 – 1000 V PV arrays)
- Optional: 4 x 2 x 4 ft. 480:480 transformer
- 3 x 7 x 10 ft. 250 kW-hr Li-ion battery
- Ramp rate control, frequency regulation, VAR support
- Seamless dynamic transfer

Courtesy: Creare, LLC

Direct Grid Connection Using SiC





<u>Limitations of this design:</u>

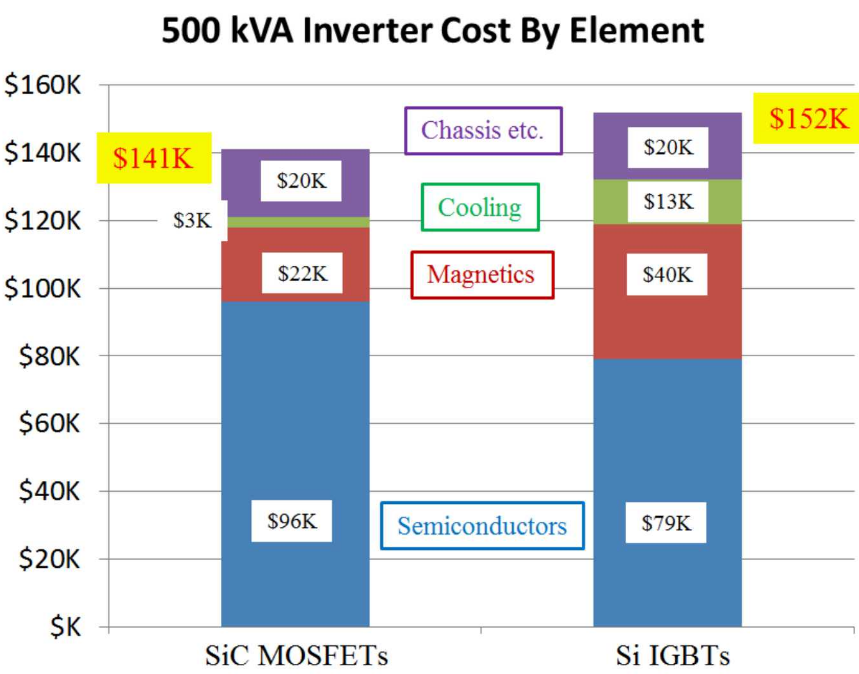
- Requires 480 : 12.47 kV transformer for grid connect.
- Silicon MOSFETs or IGBTs require liquid cooling (~ 50 ^{o}C).
- Filter is large and also requires liquid cooling.
- 60 Hz transformer emits acoustic noise.

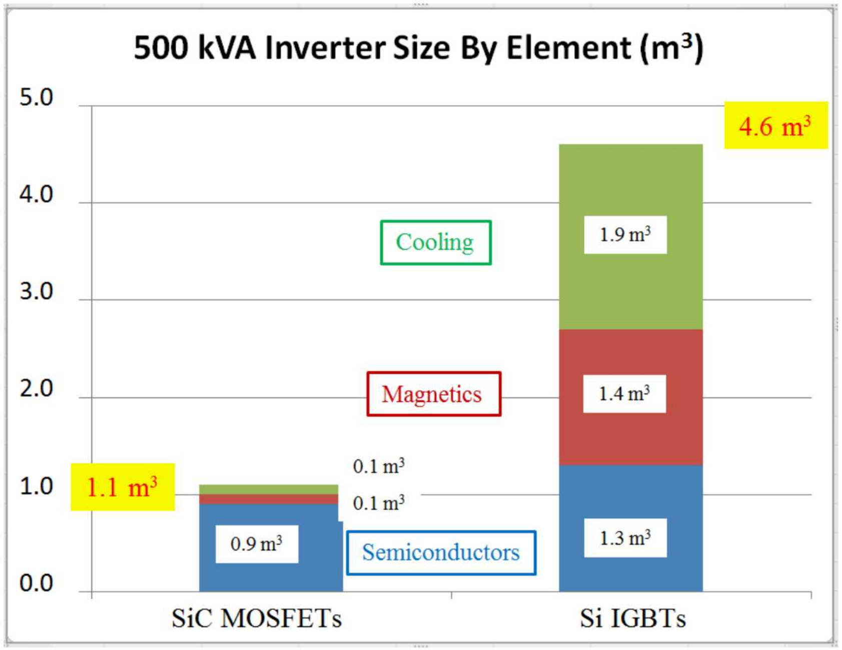
<u>Improvements:</u>

- SiC MOSFETs enable direct grid connection to 12.47 kV.
- 60 Hz transformer replaced with (2) smaller (10X) high frequency transformers.
- Transformer is quieter.
- Liquid cooling is eliminated.
- Filter faces lower current, reduces losses and eliminates liquid cooling.

Courtesy: Creare, LLC

Cost and Size Comparison: SiC vs Si





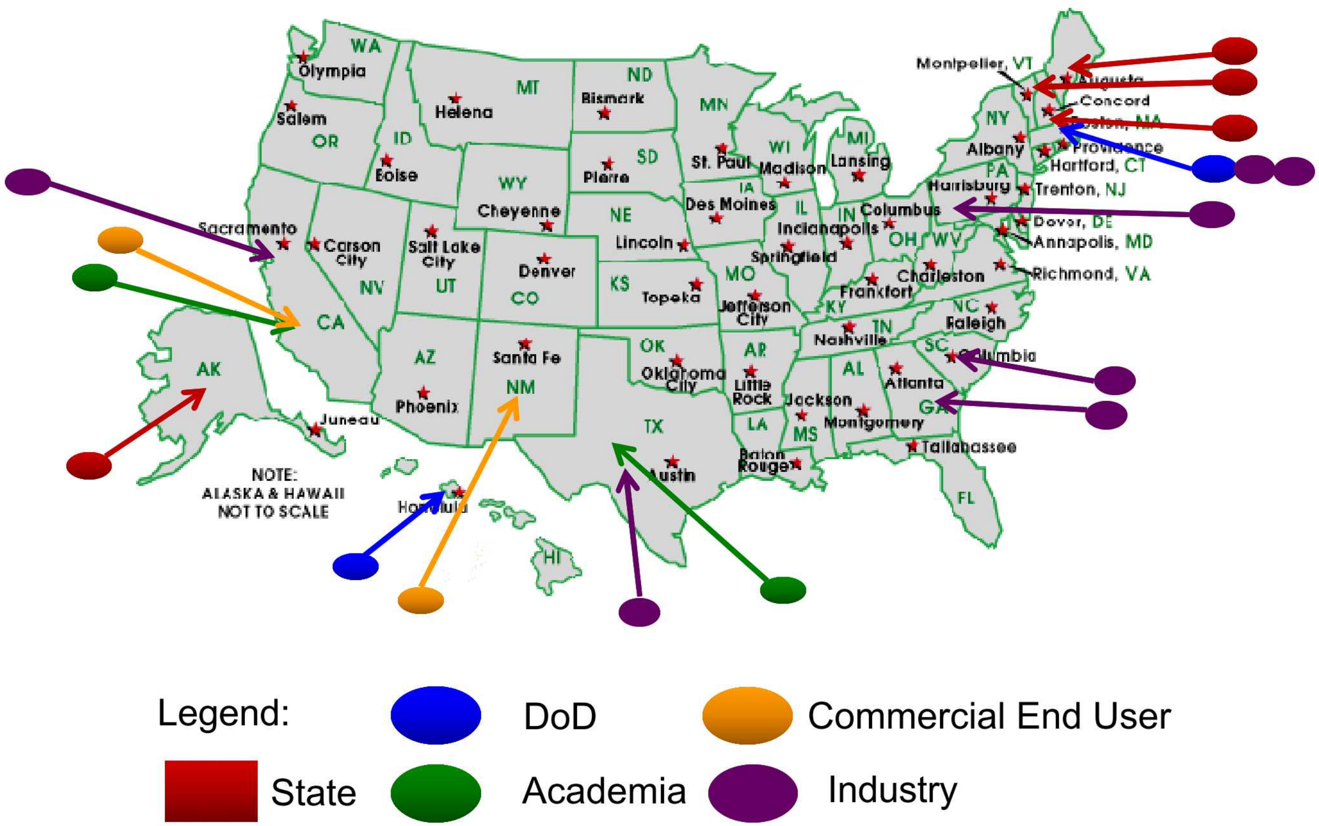
Per unit material costs are comparable ($141K vs. $152K). New design: SiC costs are higher, but magnetics and cooling costs are lower. **SiC costs are likely to reduce.**

Size of the inverter which uses SiC MOSFETs is much smaller, with 4.3X power density.

Courtesy: Creare, LLC

Field Demonstrations

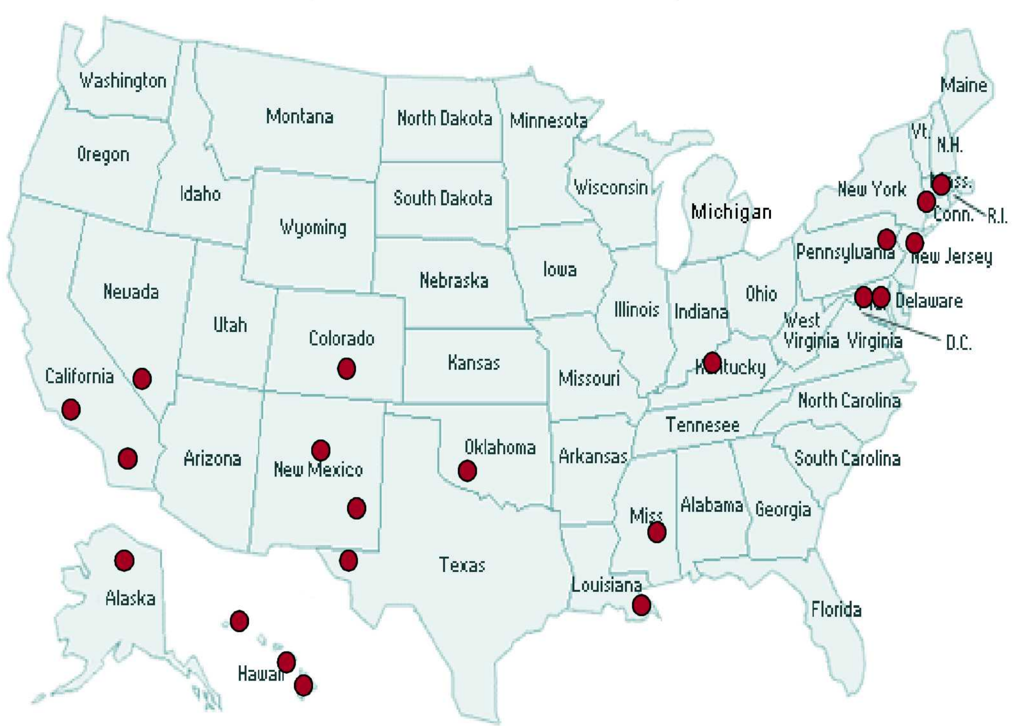
To assistance regulators and utilities in determining how to utilize storage systems to maximize return on investment (ROI). Field demonstrations and pilot projects help to ensure ROI and facilitate adoption via improving confidence in safety, reliability, performance and cost effectiveness.



Energy Surety Microgrid Efforts

Conceptual Designs/Assessments	Small Scale Microgrid Demos	Large Scale Microgrid Demos	Operational Prototypes

• Creech AFB – FY12 DoD
• Soto Cano – FY12 DoD
• West Point FY12, DoD/DOE
• Osan AFB, FY 12, DoD
• Philadelphia Navy Yard – FY11, DOE OE/PIDC
• Camp Smith – FY10, DOE FEMP
• Indian Head NWC – FY09, DOE OE/DoD
• Ft. Sill – FY08, Sandia LDRD
• Ft. Bliss – FY10, DOE FEMP
• Ft. Carson – FY10, DOE FEMP
• Ft. Devens (99th ANG) – FY09, DOE OE/DoD
• Ft. Belvoir – FY09 DOE OE/FEMP
• Cannon AFB – FY11, DOE OE/DoD
• Vandenberg AFB – FY11, DOE FEMP
• Kirtland AFB – FY10, DOE OE/DoD
• Maxwell AFB – FY09, DoD/DOE
• Alaska Villages– FY12, DOE
• Bagram – FY13, DoD
• Kuwait – FY15, DoD
• 29 Palms – FY14, DoD
• Korea Naval Academy – FY16, DoD
• Kaui – FY15, DOE
• Northhampton, MA – FY14, DOE
• New Orleans – FY17, DOE
• UPS in KY – FY17, DOE
	• Maxwell AFB – FY09, DoD
	• Ft. Sill – FY09, DoD w/ SNL serving as advisor
		• SPIDERS JCTD – FY11, DOE/DoD
		  • Camp Smith
		  • Ft Carson
		  • Hickam AFB
			• H.R. 5136 National Defense Authorization Act



Navajo Tribe - Remote Power Systems

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