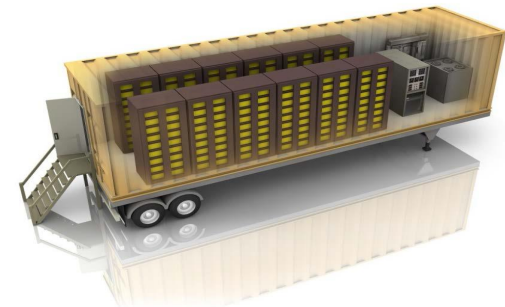
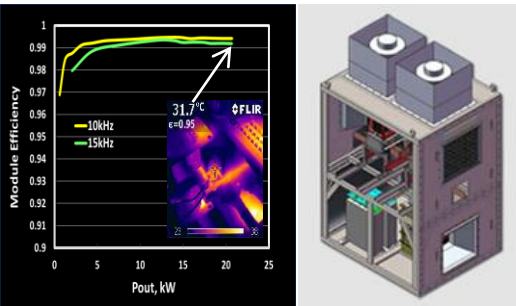


The Role of Power Conversion Systems for Grid-Tied Energy Storage



Stan Atcitty

*Energy Storage Technology and Systems
Department 06111*

Sandia National Laboratories



*Exceptional
service
in the
national
interest*



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DOE Office of Electricity Energy Storage Program

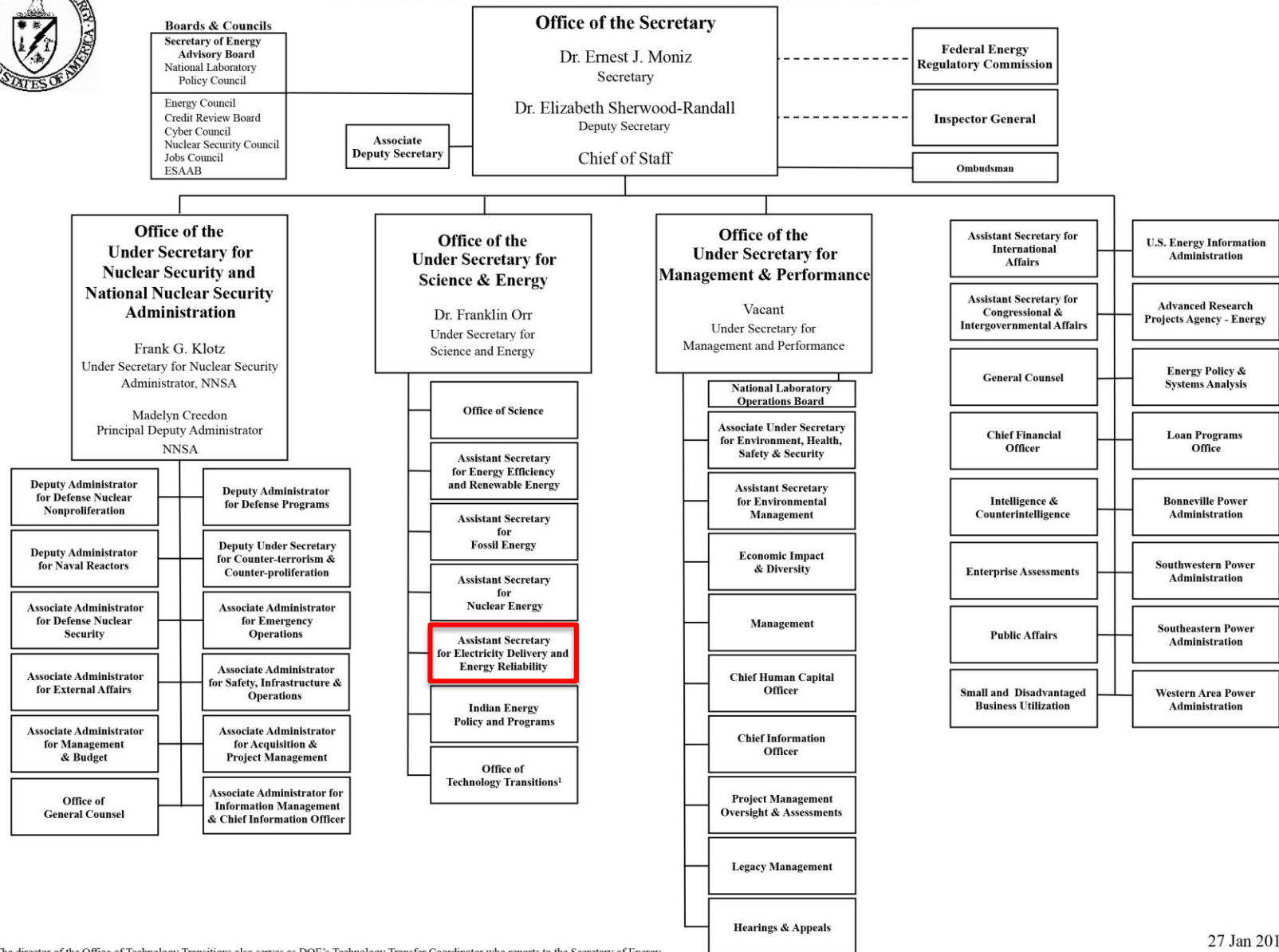


- The goal of the Energy Storage Program is to develop advanced energy storage technologies and systems, in collaboration with industry, academia, and government institutions that will increase the reliability, performance, and competitiveness of electricity generation and transmission in the electric grid and in standalone systems.
- This program is part of the DOE Office of Electricity Delivery and Energy Reliability.
- The Energy Storage Program is managed by Dr. Imre Gyuk.

<http://www.sandia.gov/ess/>



DEPARTMENT OF ENERGY



27 Jan 2016

Sandia National Laboratories

Albuquerque, New Mexico



Livermore, California



Kauai, Hawaii



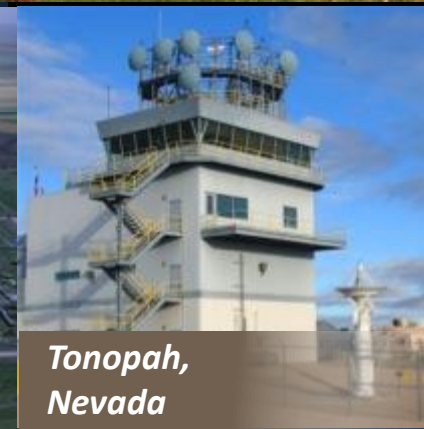
*Waste Isolation Pilot Plant,
Carlsbad, New Mexico*



*Pantex Plant,
Amarillo, Texas*



*Tonopah,
Nevada*



Energy & Climate

Energy Research

ARPAe, BES Chem Sciences, ASCR, CINT, Geo Bio Science, BES Material Science

Climate & Environment

Measurement & Modeling, Carbon Management, Water & Environment, and Biofuels

Nuclear Energy & Fuel Cycle

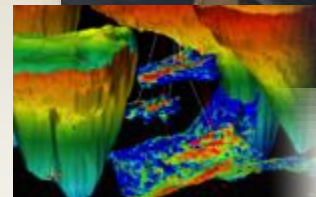
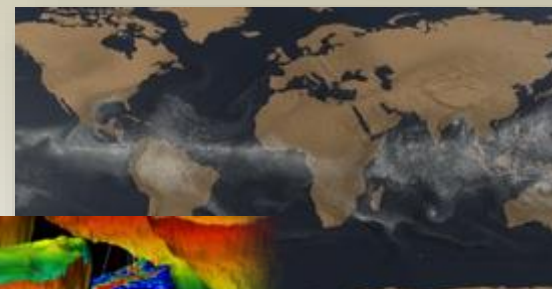
Commercial Nuclear Power & Fuel, Nuclear Energy Safety & Security, DOE Managed Nuclear Waste Disposal

Renewable Systems & Energy Infrastructure

Renewable Energy, Energy Efficiency, Grid and Storage Systems

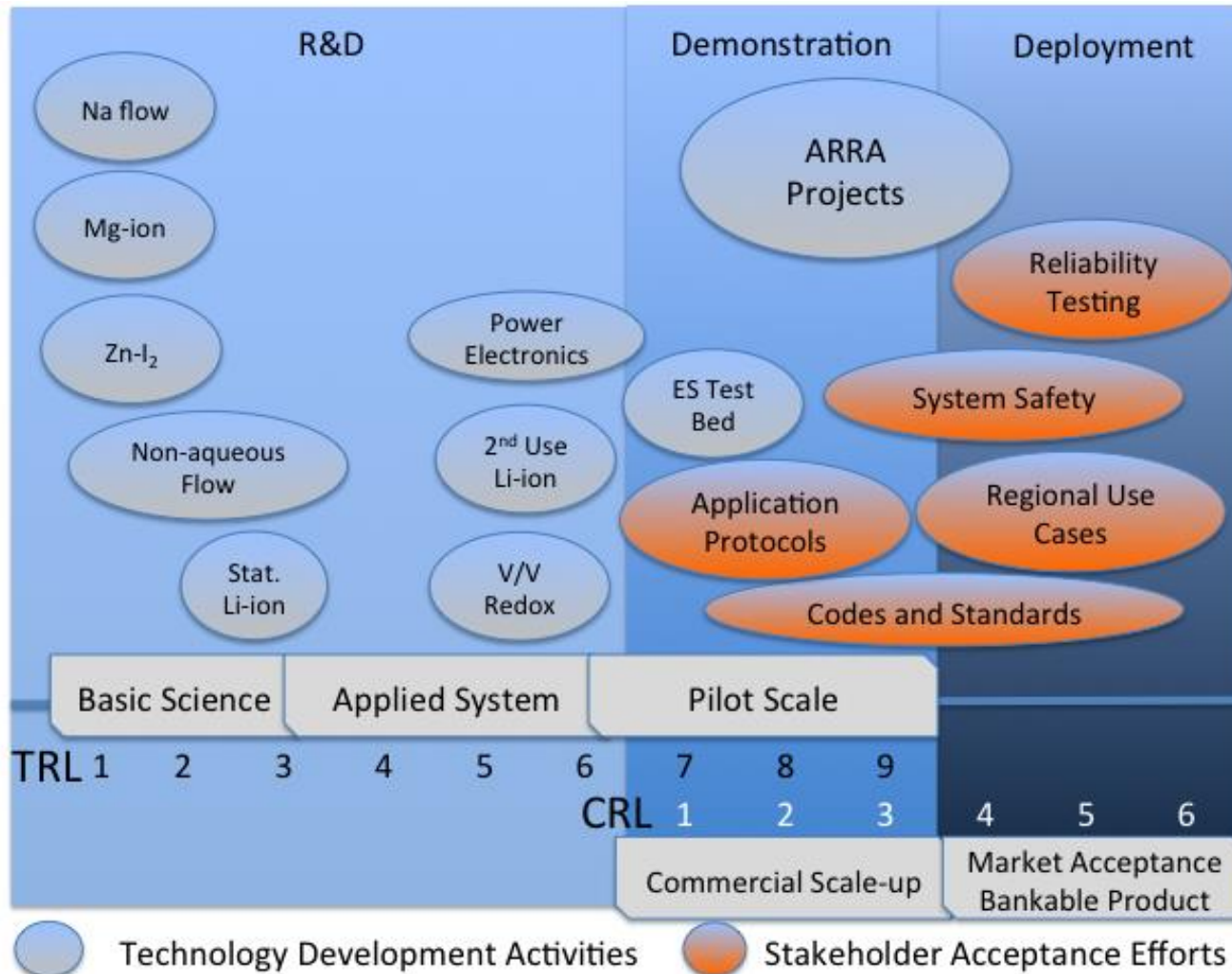
Transportation Energy & Systems

Vehicle Technologies, Biomass, Fuel Cells & Hydrogen Technology



OE Energy Storage Program Scope

To accelerate the development and adoption of energy storage the OE-Energy Storage Program is working across the entire technology development cycle



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

Traditional Grid

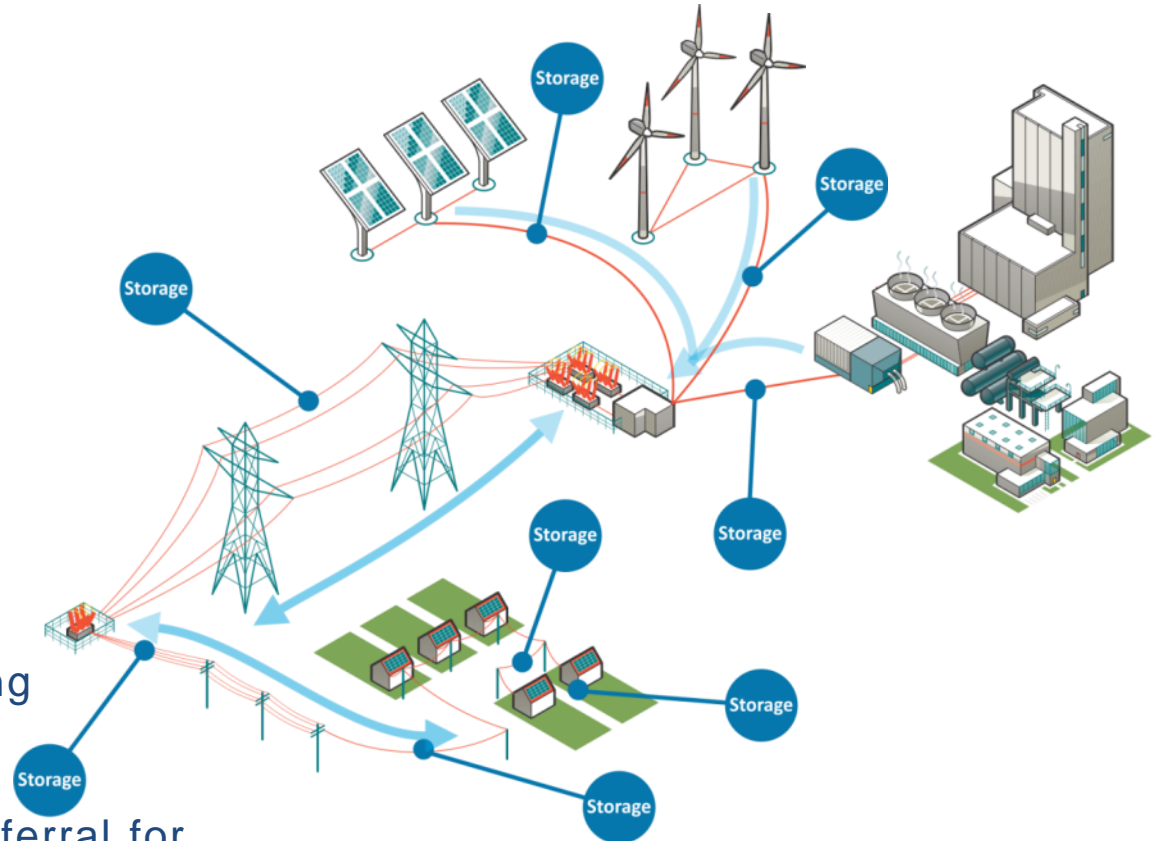
- One way flow
- Little/no renewable energy

Today's Grid

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

Future Grid

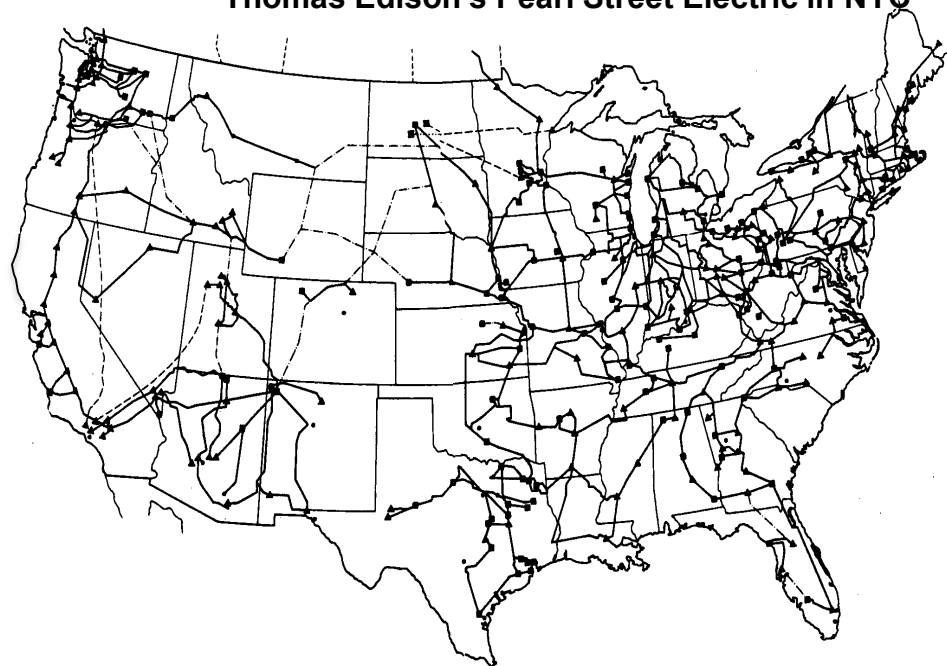
- Storage provides buffering capability to enable high penetration of variable renewables and asset deferral for T&D systems (load management, ancillary services)
- Efficient two-way flow



Electric Utility Background

First modern electric system developed in 1882 by
Thomas Edison's Pearl Street Electric in NYC

Common AC voltages	
Transmission	765kV
	500kV
	345kV
	230kV
Sub-Transmission	69kV
	30kV
	15kV
	4kV
Distribution	2kV
	600V
	480V
	240V
	120V



Made up of:

- Over 150 thousand miles of transmission lines (AC & DC)
- 10s of thousands of Generating Units totaling ~1000GW of total capacity
- Millions of transformers, relays, and controls
- 100s of Billions of dollars in total investments in transmission and distribution

Electric Utility Major Blackouts

- Northeast Power Blackout August 14, 2003



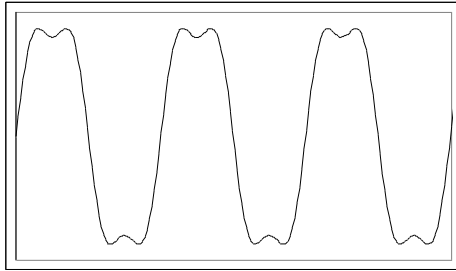
Source: http://www.globalsecurity.org/eye/blackout_2003.htm

~50M people effected

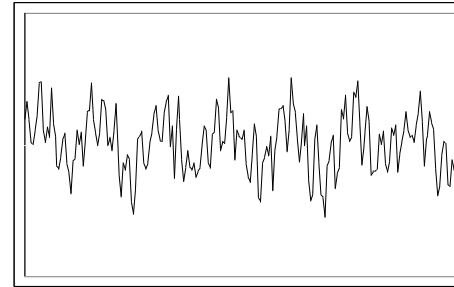
~6Billion in financial losses

- Western US Blackout August 1996
 - High demand, heat wave, and sagging power lines
- New York City Blackout July 1977
- Northeast Blackout November 1965

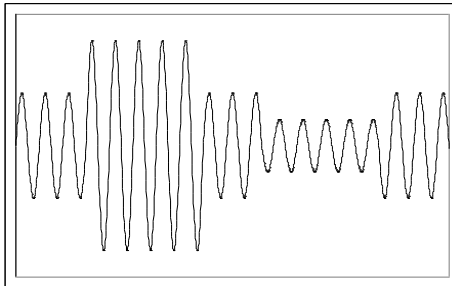
Other Electric Utility Challenges



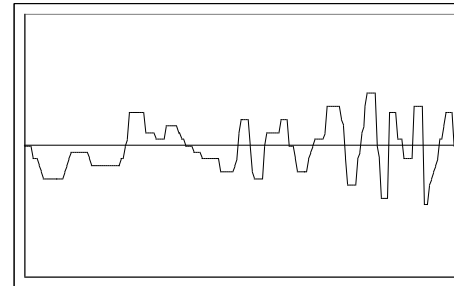
Harmonic Distortion



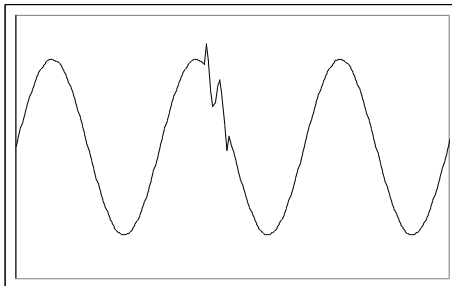
Voltage Flickers



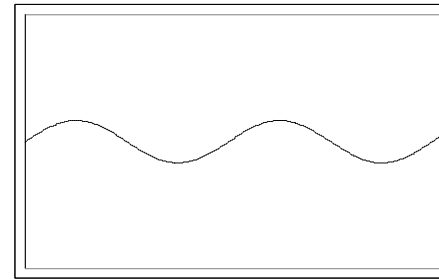
Voltage Swells & Sags



Frequency Oscillations



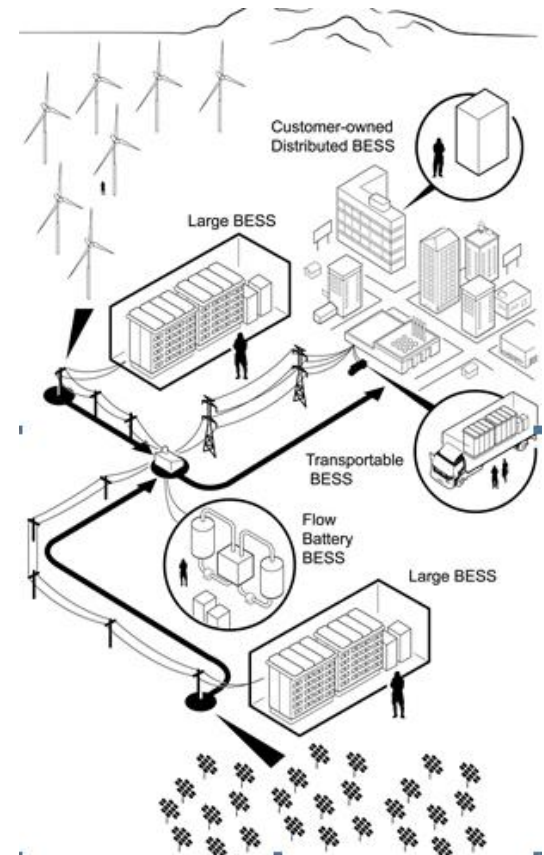
Oscillatory Transients



Subsynchronous Resonance

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



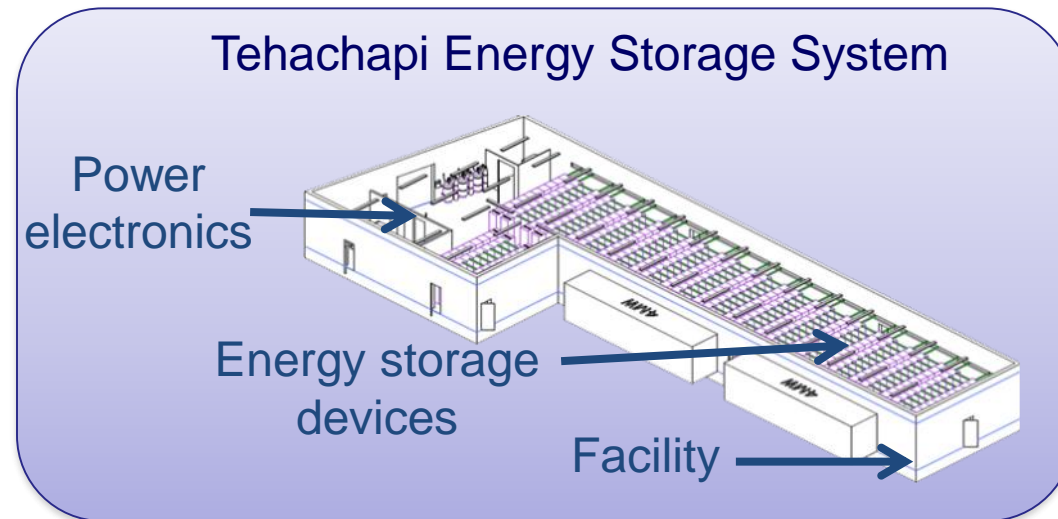
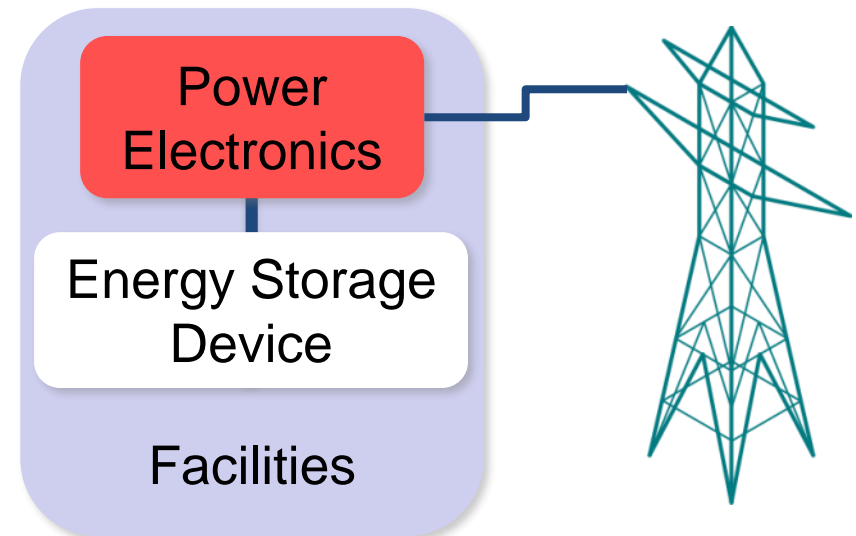
Source: Power Electronics for Renewable and Distributed Energy Systems: A Sourcebook of Topologies, Control and Integration

Energy Storage System Configuration

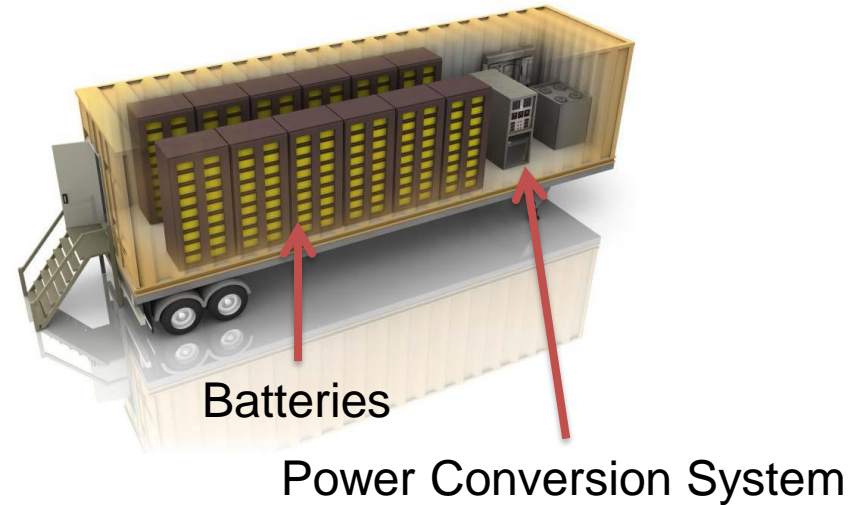
Energy Storage Systems contain three major components:

- 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



Transportable Energy Storage Systems

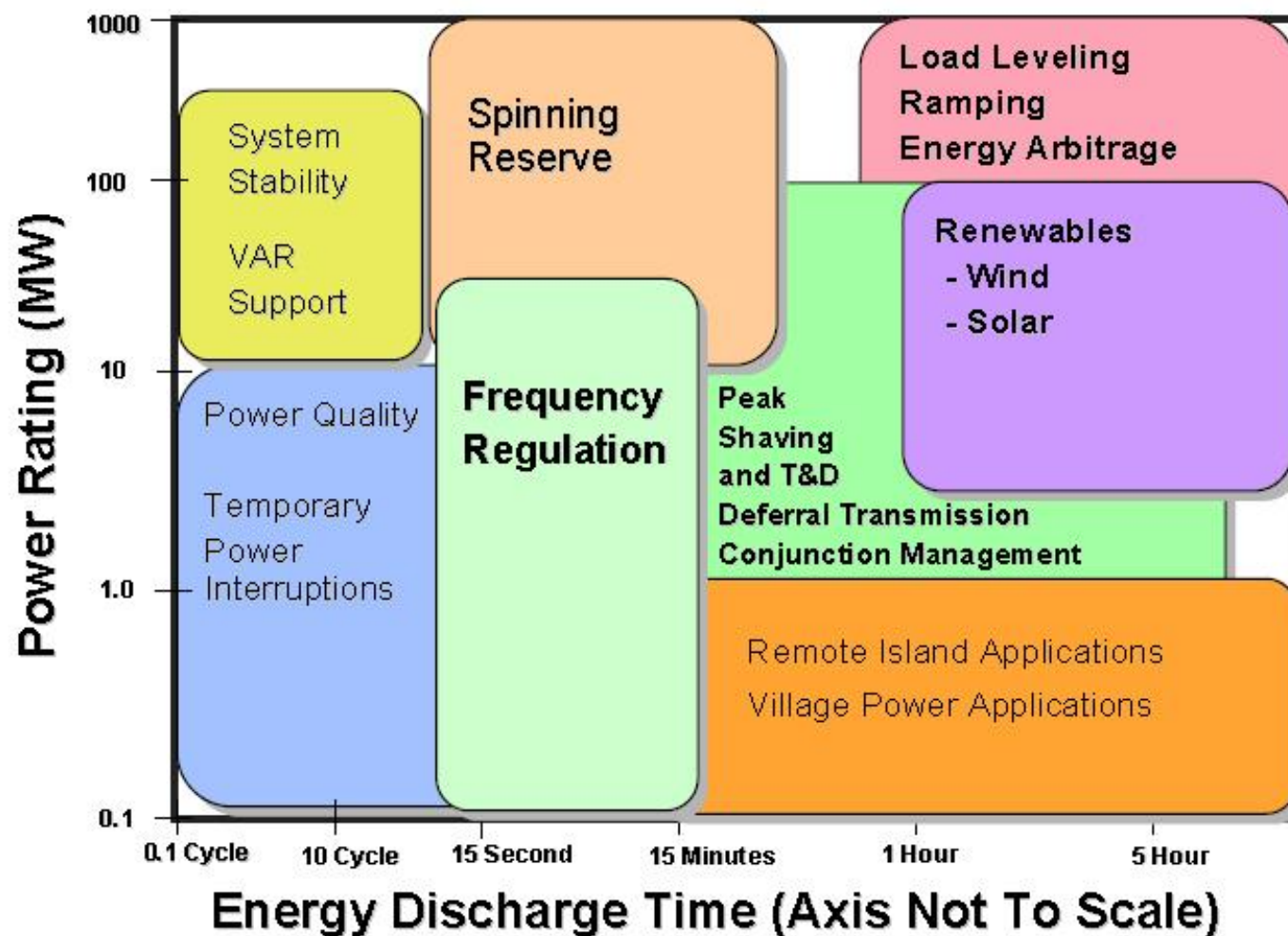


Benefits

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



Power and Energy



Source: Electric Power Research Institute

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

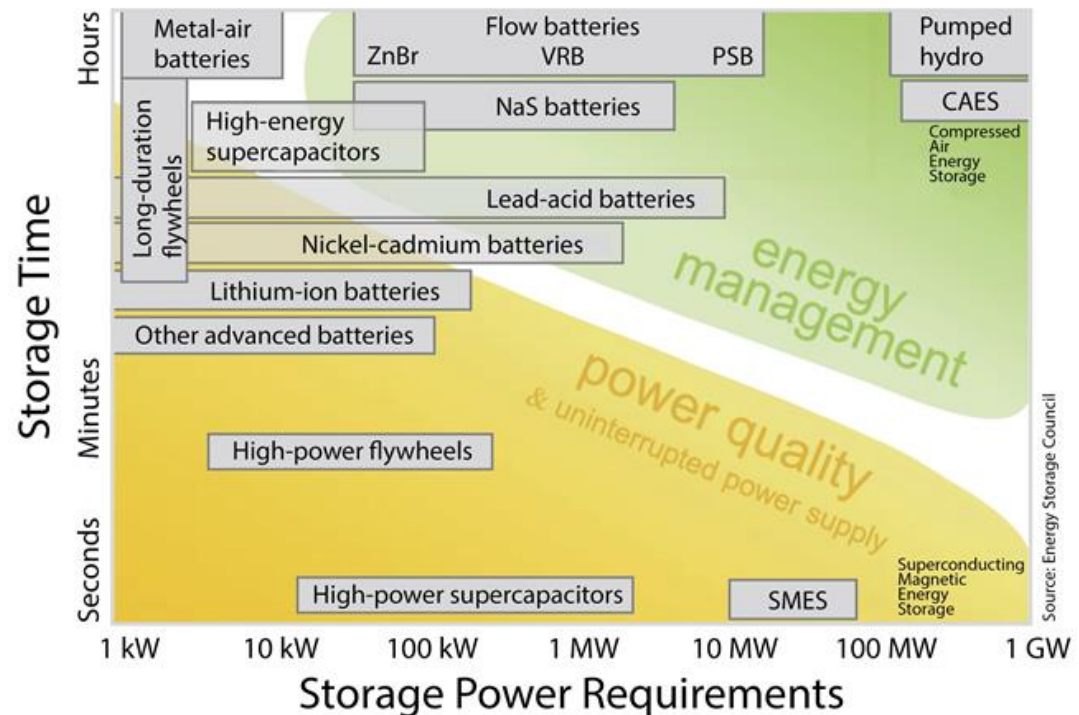
Two regimes, multiple technologies:

Power – short discharges (sec to min):

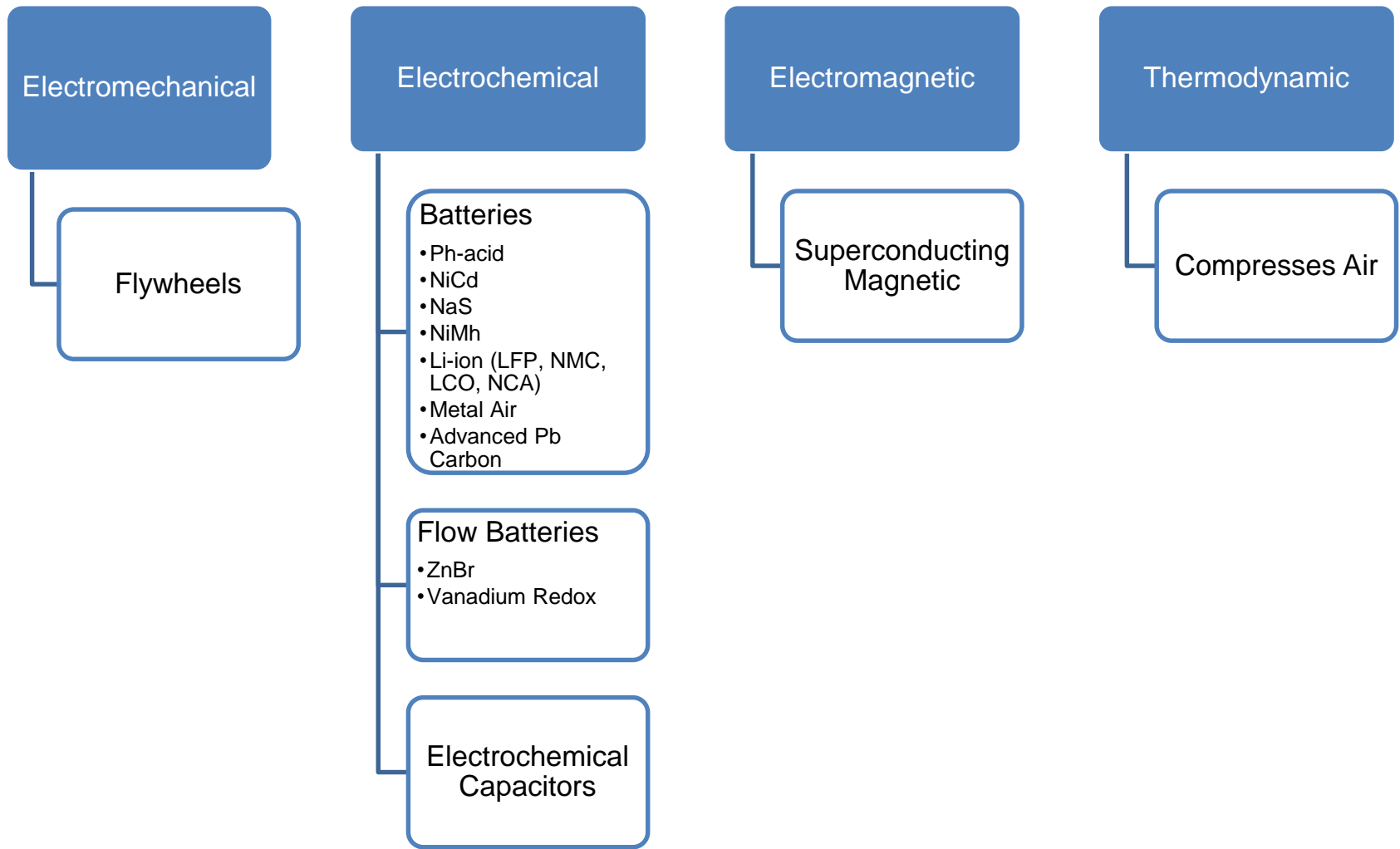
flywheels, capacitors, SMES, some batteries

Energy – long discharges (min to hr):

batteries, CAES, pumped hydro



Energy Storage Classification

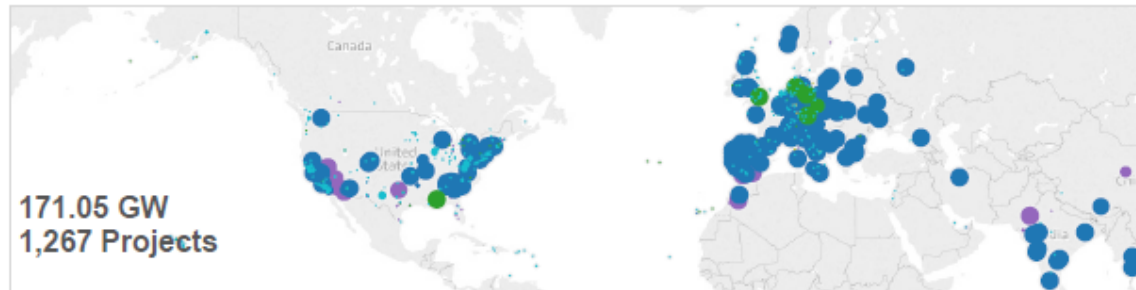
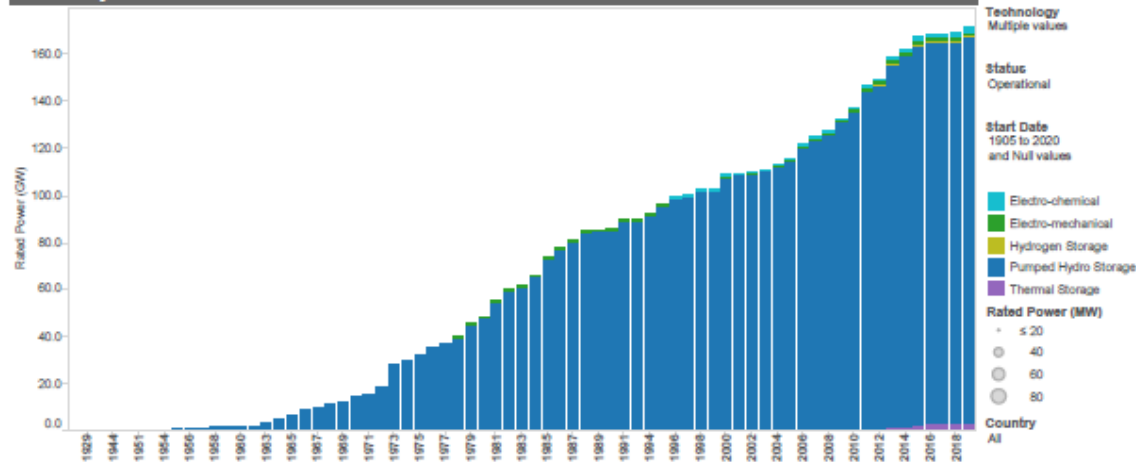


DOE Global Energy Storage Database

DOE Global Energy Storage Database

Last Updated 8/16/2016 1:25:38 PM

Global Project Installations Over Time



The DOE Global Energy Storage Database (<http://www.energystorageexchange.org>) is powered by Sandia Corporation (<http://www.sandia.gov>) and Stratagen Consulting, LLC (<http://stratagen.com>)



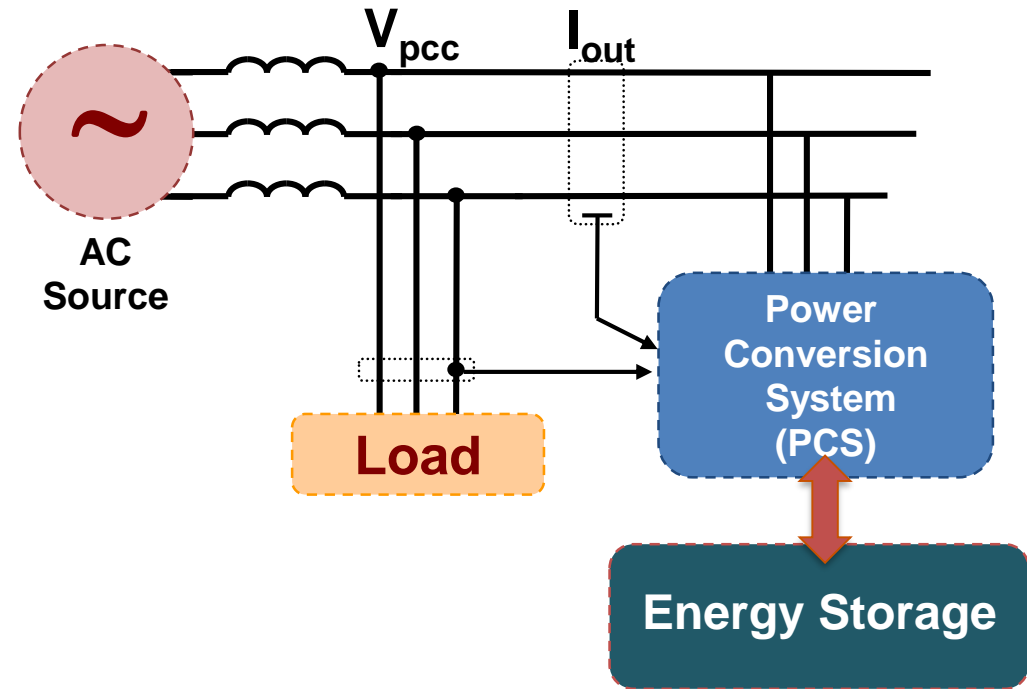
DOE Energy Storage Database
www.energystorageexchange.org

DOE Database (since 2012)

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

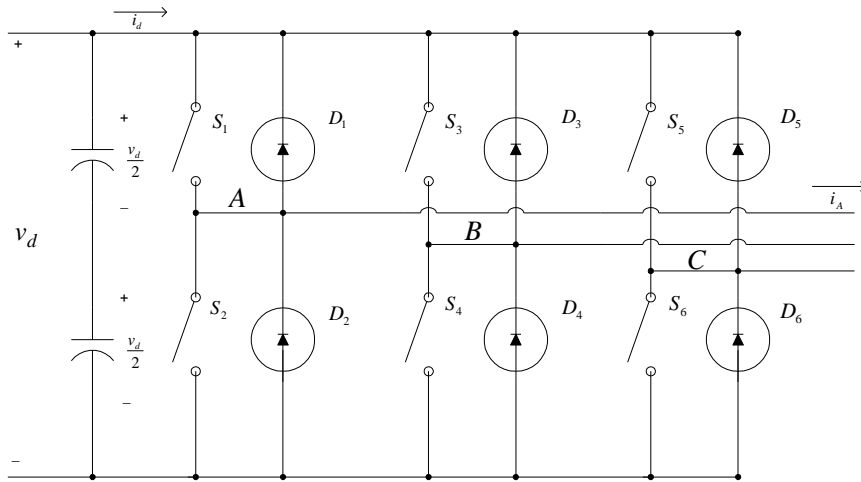
Why is DOE OE/Sandia interested in power electronics?

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



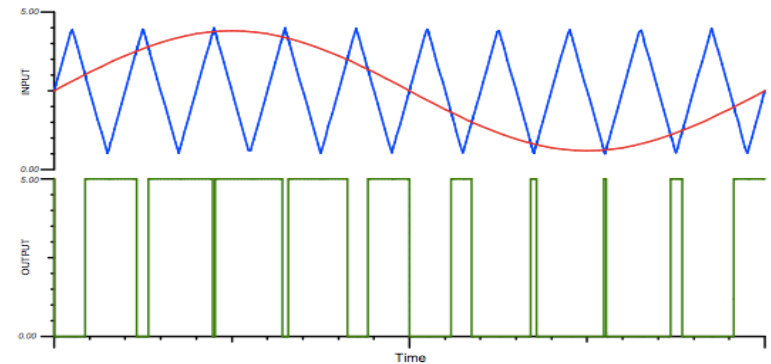
**The PCS is a key component of the energy storage system.
It can represent 20 to 60% of the total system cost.**

Power Conversion System

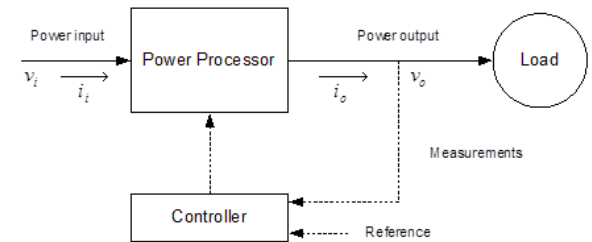


Three-phase inverter

- Power Electronics – AC/AC, DC/DC, DC/AC, AC/DC
- Heart of the system – semiconductor switches
- PWM signal is constructed. The sawtooth wave and reference signal are compared in a controller shown in the block diagram. The resulting PWM signal is sent to the Power Processor



Construction of a PWM signal (output of a comparator (green) with a sawtooth wave (blue) and a reference signal (red))



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



18650 Cell

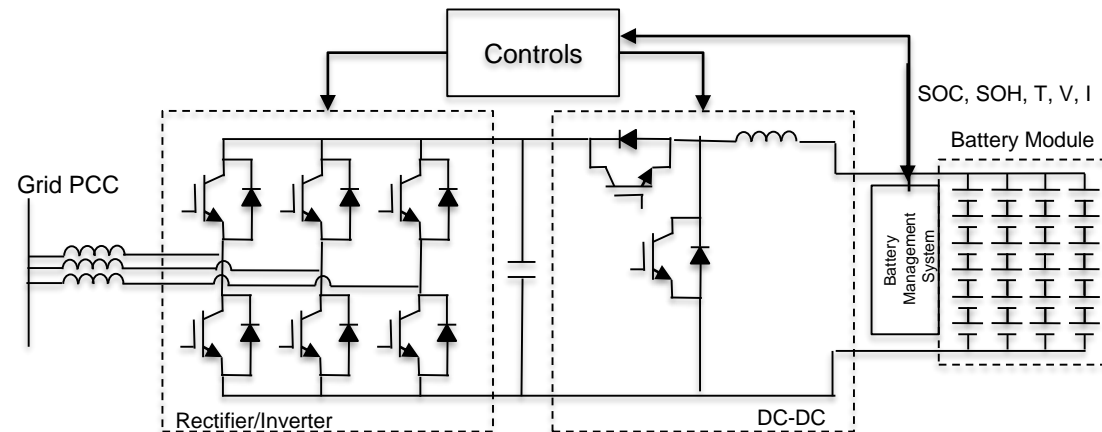


Benefits

- Applications – wide spectrum from PQ to peak shaving
- Power & energy range, few kW to 10s MW

Challenges

- Power conversion system, batteries, grid interconnect
- Reliability, safety, round trip efficiencies



Typical Electrical Configuration of a BESS

Flywheel Energy Storage System

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

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

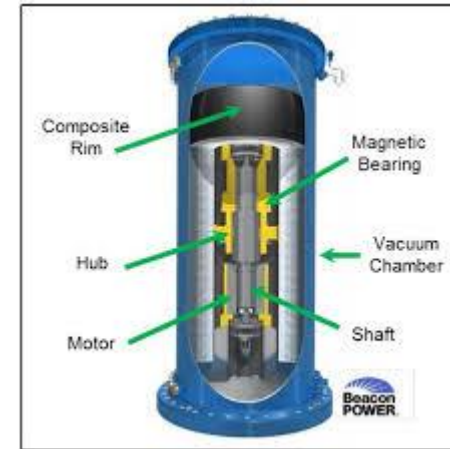
$$I = \frac{1}{2} m(r_1^2 + r_2^2)$$

$\omega = \text{angular velocity}$

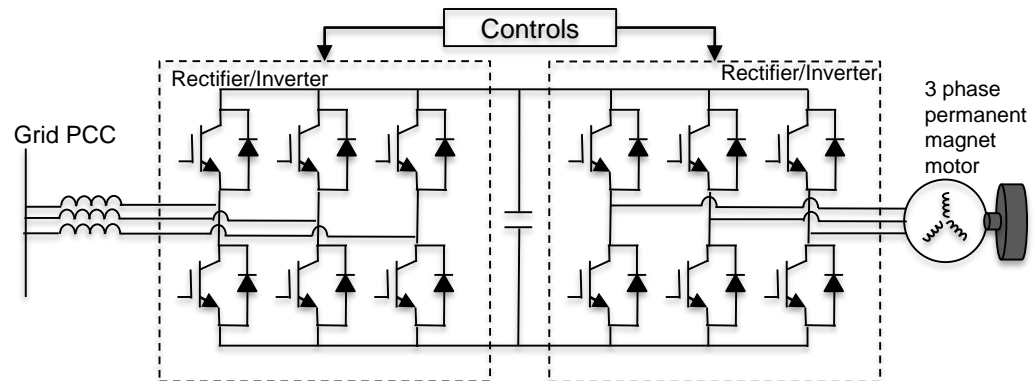
$I = \text{moment of inertia}$

$m = \text{mass}$

$r = \text{radius}$



Source: Beacon Power, LLC



Typical Electrical Configuration of a FWES

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

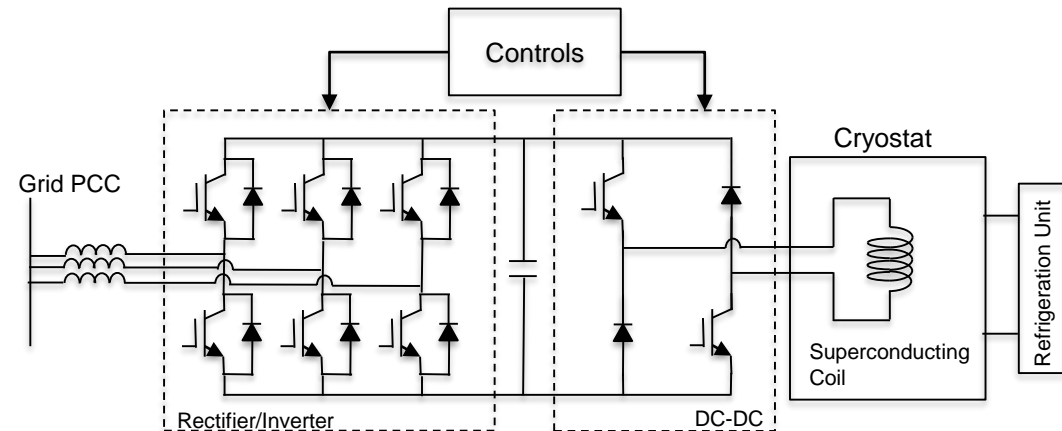
- High frequency composite FW -> high BW power conversion system
- Balance of system cost

Superconducting Magnetic Energy Storage System

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



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

Background

- Magnetic energy storage device
- Energy stored in magnetic field generated by the current in the superconducting coil (i.e. $R \sim 0$ ohms). Energy released when coil is discharged.
- Since $R \sim 0$ 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

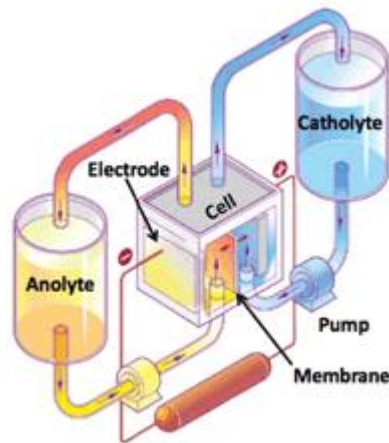
Challenges

- Balance of system cost
- Low energy density

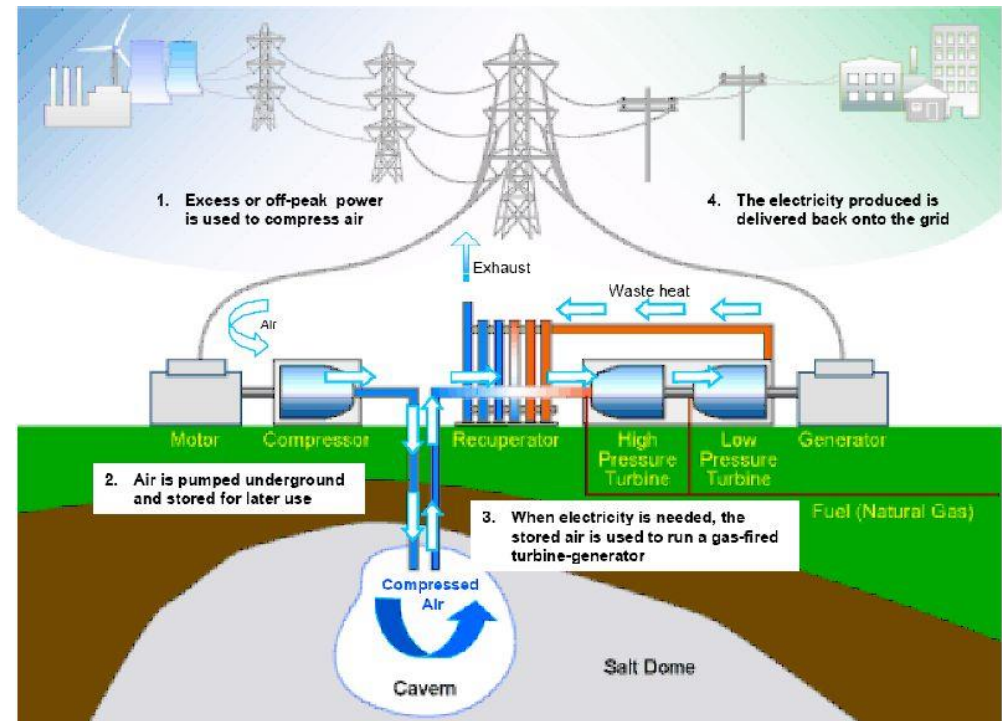
Other Energy Storage Technologies



Electrochemical Capacitor Energy Storage



Flow Battery Energy Storage

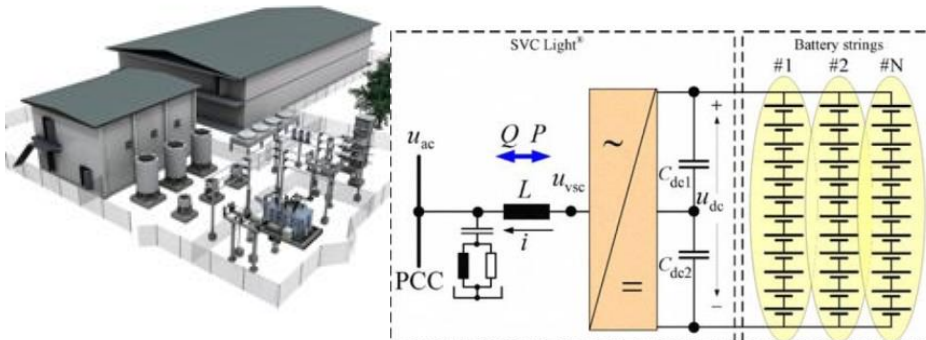


Compressed Air Energy Storage

Examples of Large Energy Storage Demonstrations

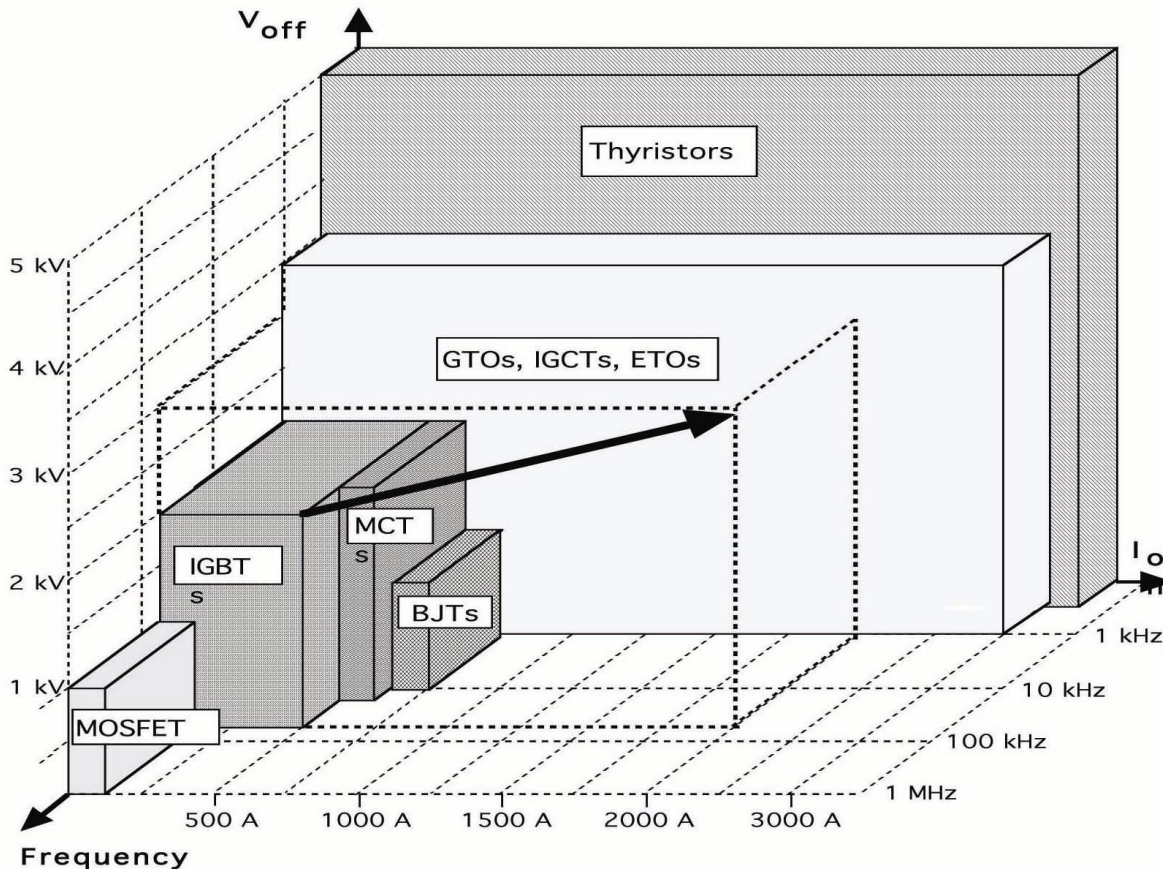


- Golden Valley Electric Authority (GVEA), Fairbanks, Alaska
 - Ni-Cd Battery (5kV, 3.68kAh)
 - 46 MW for 5 minutes
 - ABB power electronics



- SVC light pilot system near Norfolk, England
 - Li-ion (5.8kV, 200kWh)
 - 600kW for 15 minutes
 - ABB power electronics

Silicon Semiconductor Device Capabilities



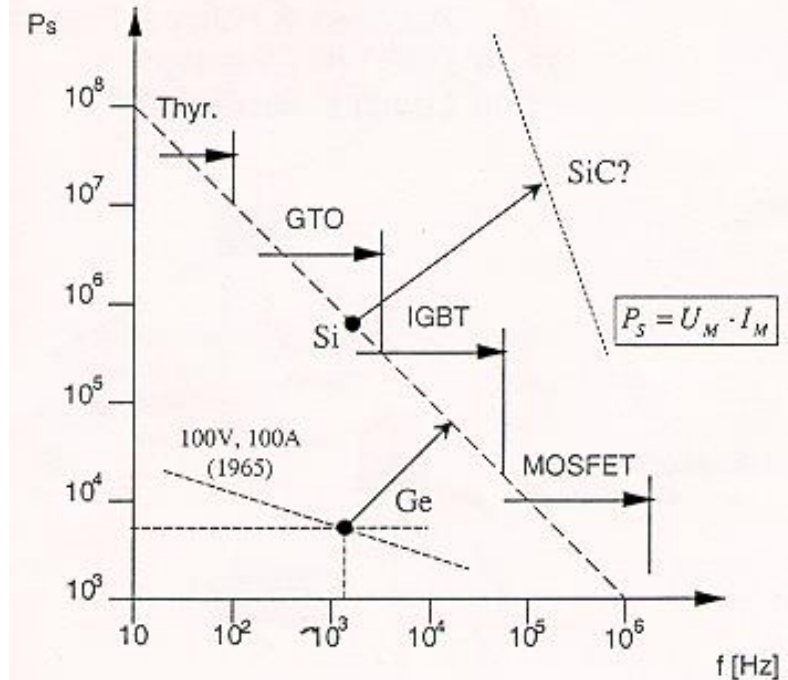
Trends:

- Increase Voltage/Current Ratings
- Increase Switching Frequency
- Lower Switching Losses
- Improve Drives
- More Integration
 - Self Protection & Diagnostics
- Lower Inductance

Source: Mohan, Undeland, and Robbins, Power Electronics: Converters, Applications and Design 3rd Edition (John Wiley & Sons, 2002)

WBG device benefits

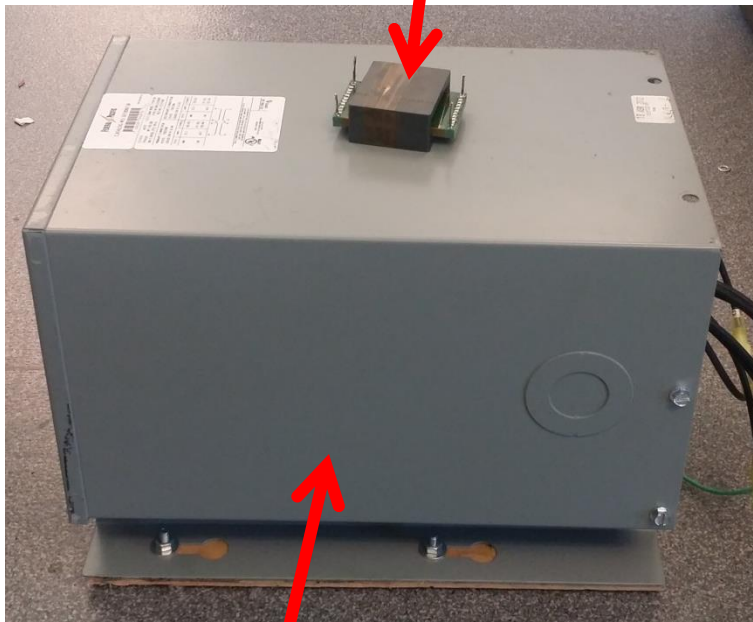
- Advantages
 - High Frequency Operation
 - Lower Switching Losses
 - Higher Blocking Voltages
 - Higher Operating Temperature
 - Higher Efficiencies
- Disadvantages
 - Expensive
 - Limited Current Level



Source: Power Electronics Technology at the Dawn of the New Millenium – Status & Future

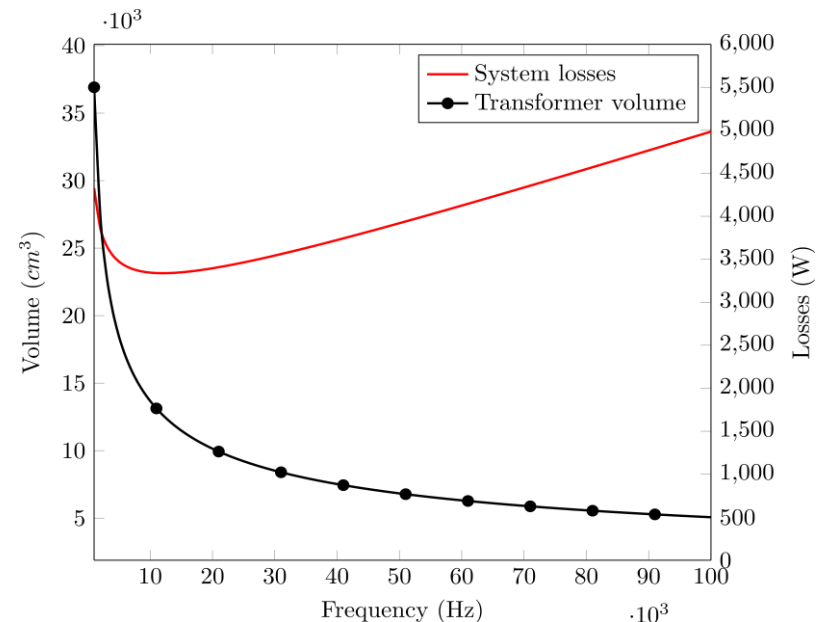
High Switching Frequency Benefits

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



60 Hz Si-Steel Transformer
7.5 kVA – 150 lbs

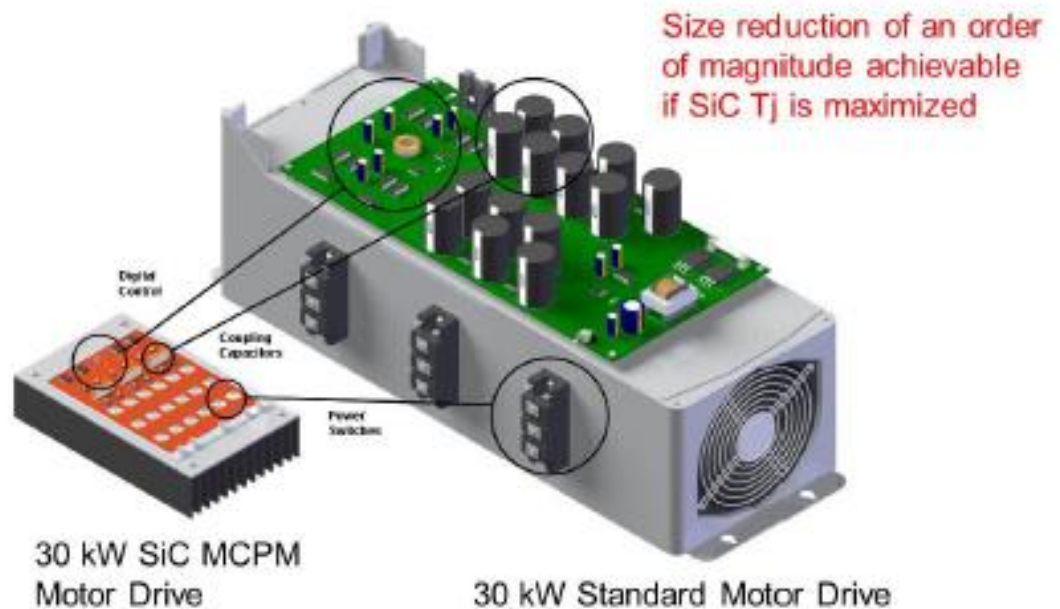
Source: Wolfspeed



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

Example Benefit of Using SiC switches

- Miniaturize power electronics systems by employing WBG power devices in high temperature and high efficiency design
- Passive cooling
- Higher switching frequency



Source: Wolfspeed

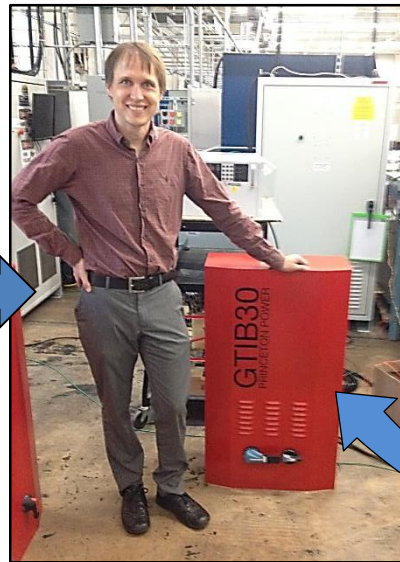
Example: 30kW SiC Inverter



30kW Bidirectional Inverters

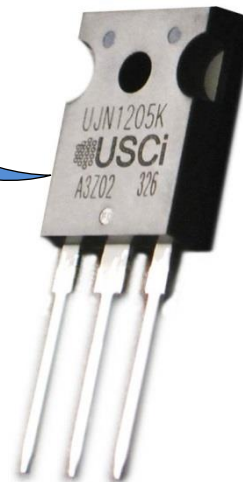


1200V Si-IGBT
6kHz
Floor Mount



1200V SiC-JFET
20kHz
Wall Mount

- Power Density Increase by >3X due to faster switching – From 6kHz to 20kHz
- Peak Efficiency Increase of ~ 2%
- Power stage uses USCi 1200V SiC-JFET



UJN1208K TO-247

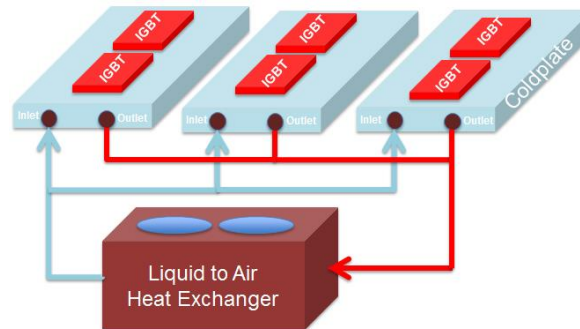
Parameter	Value	Unit
$R_{DS(on)}$	80	m Ω
V_{DS}	1200	V
T_{max}	175	$^{\circ}\text{C}$

Source: USCi

Thermal Management Reduction



Source: EPC Power Corporation



Source: Aavid Thermalloy

- Current energy storage PCS use complex liquid cooling systems or hybridized liquid/forced air systems for the semiconductor switches and magnetics
 - Bulky
 - Maintenance cost can be high
- WBG devices along with peripheral components having a higher temperature operation can reduce thermal management requirements
 - Less efficient but smaller and cheaper cooling systems can be used resulting in higher power density PCS designs
 - Lower maintenance cost

DOE OE Power Electronics Development



WORLD'S FIRST FIBER OPTIC ELECTRICAL TRANSDUCER TO PASS MILITARY VIBRATION AND SHOCK CERTIFICATION

Exceeds 30Mhz
Capable of Operating up to 34.5kV without additional Insulation, Isolation, or Cooling



WORLD'S FIRST HIGH TEMPERATURE SiC SINGLE-PHASE INVERTER

3 kW (1200 V/150 A peak)
250 °C Junction Temperature
Integrated Gate Driver



WORLD'S FIRST HIGH TEMPERATURE SiC POWER MODULE

50 kW (1200 V/150 A peak)
250 °C Junction Temperature
Integrated HTSOI Gate Driver



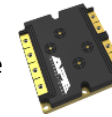
WORLD'S FIRST COMMERCIALY AVAILABLE ULTRA-HIGH-VOLTAGE SiC THYRISTOR

Rating exceed 6.5kV, 200kHz, 80A
> 200°C junction temperature



WORLD'S FIRST HIGH VOLTAGE, HIGH TEMPERATURE, REWORKABLE SiC HALF-BRIDGE POWER MODULE

> 15 kV / 100 A, > 200 °C Reworkable
Wire Bond Free, Low Parasitic Design
Device Neutral HV Isolated Gate Driver



WORLD'S HIGHEST VOLTAGE NORMALLY OFF SiC JFET

6.5 kV, 20kHz, 60A
200°C Junction Temperature



WORLD'S FIRST VOLTAGE CONTROLLED 4500V/400A TURN-OFF THYRISTOR

4500V and 400A rated
Integrated Si MOSFET and GTO
Embedded Current Sensing Capability



WORLD'S FIRST HIGHLY ACCELERATED LIFETIME TESTING (HALT) OF HIGH VOLTAGE SiC MODULES

Dramatically Accelerates Design Cycle
-100 °C to 250 °C (1.7 °C/s Ramp)
48 in × 48 in Table Size
6 axis 75 gRMS Vibration



WORLD'S FIRST MONOLITHICALLY INTEGRATED SINGLE CHIP TRANSISTOR

Integrated SJT/Diode Chip at 1200V

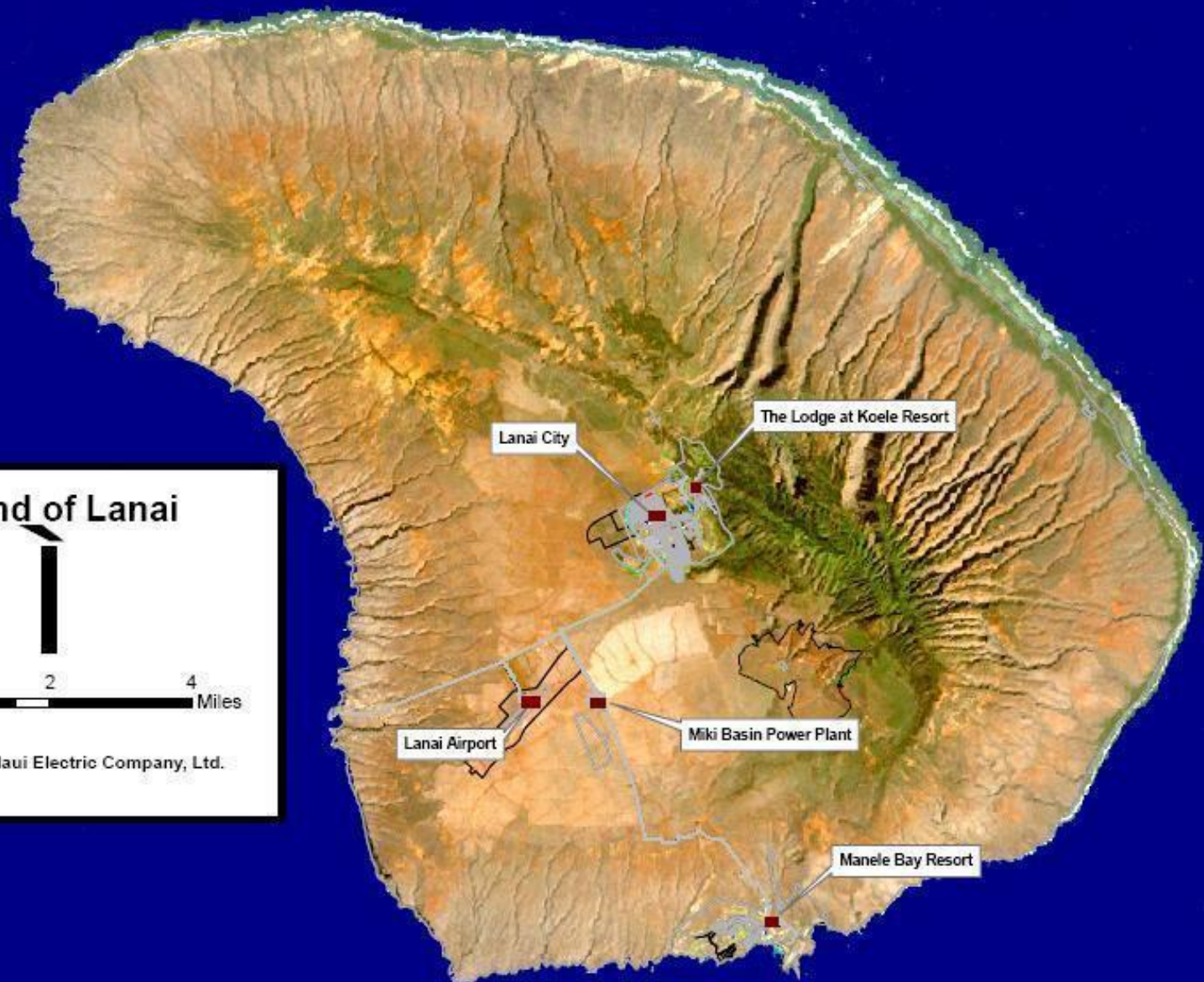
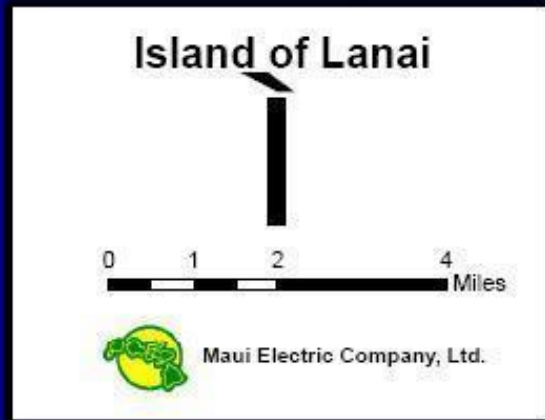


WORLD'S FIRST HIGH FREQUENCY, HIGH TEMPERATURE, SiC HALF-BRIDGE POWER MODULE

15 kV/100 A, 20 kHz, 200C Reworkable
Low Parasitic Design
Device Neutral HV Isolated Gate Driver



Lanai Battery Project





(6) 1.0 MW EMD Diesel
Generators
(2) 2.2 MW Caterpillar Diesel



Miki Rd

La Ola PV Station



Kaupili Rd

7,000 PV Panels; 1.2 MW output
Dedicated January 6, 2009



Variability of PV Output

Graphs

Lifetime

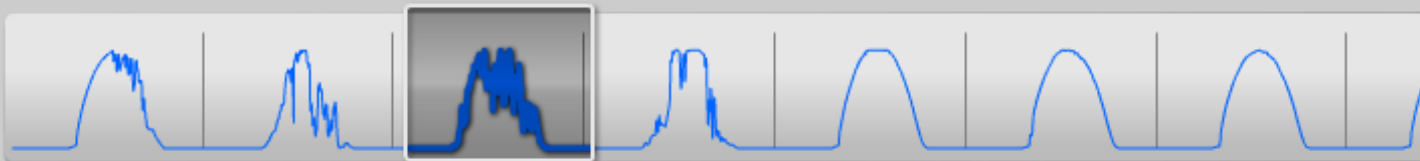
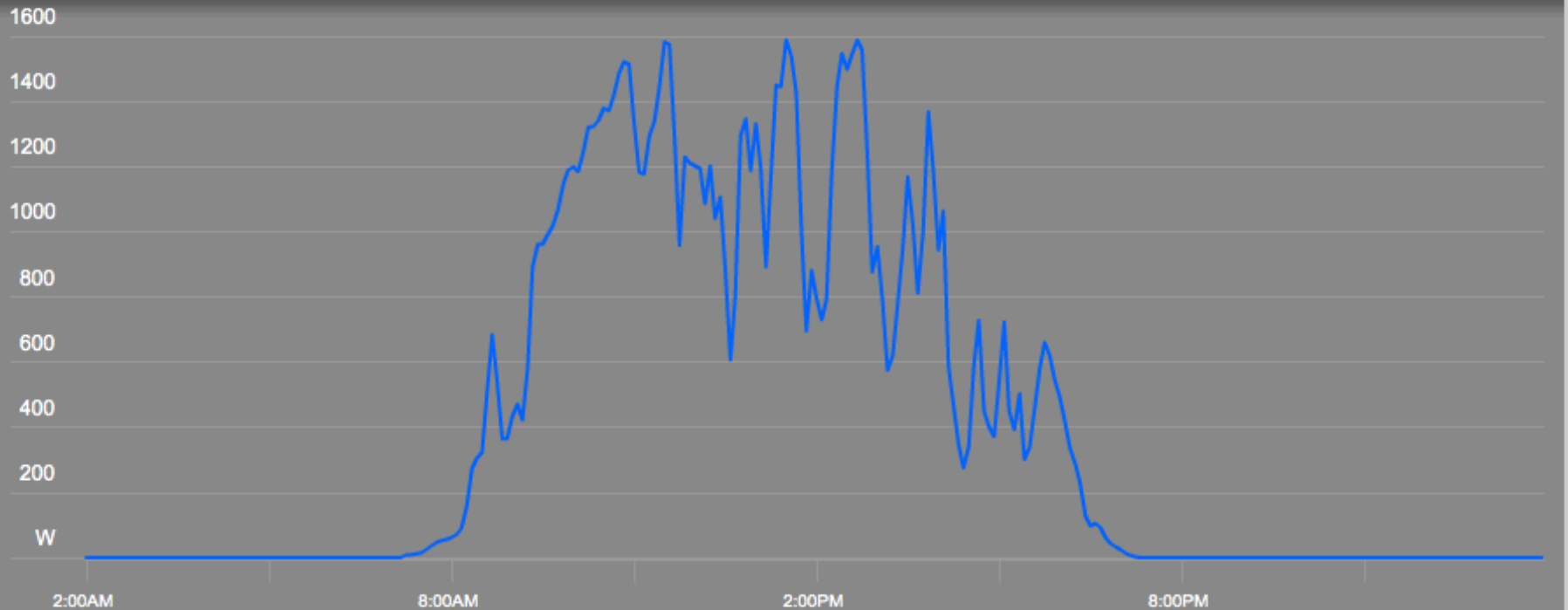
12 months

8 weeks

4 weeks

7 days

24 hours



Mon Mar 19 2012 1:58AM - Tue Mar 20 2012 1:58AM MDT

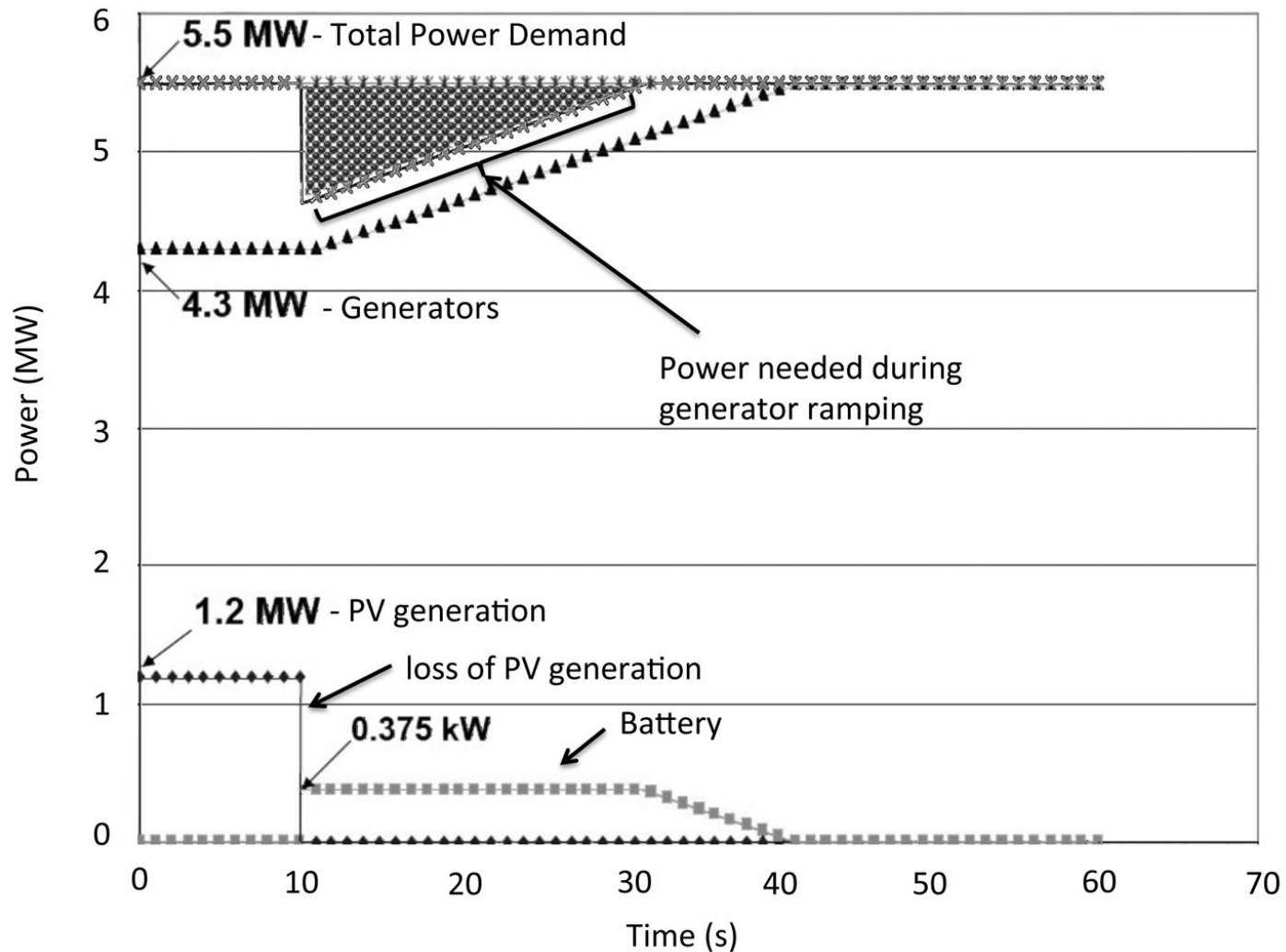
Total Energy = 9.56 kWh

Power Produced

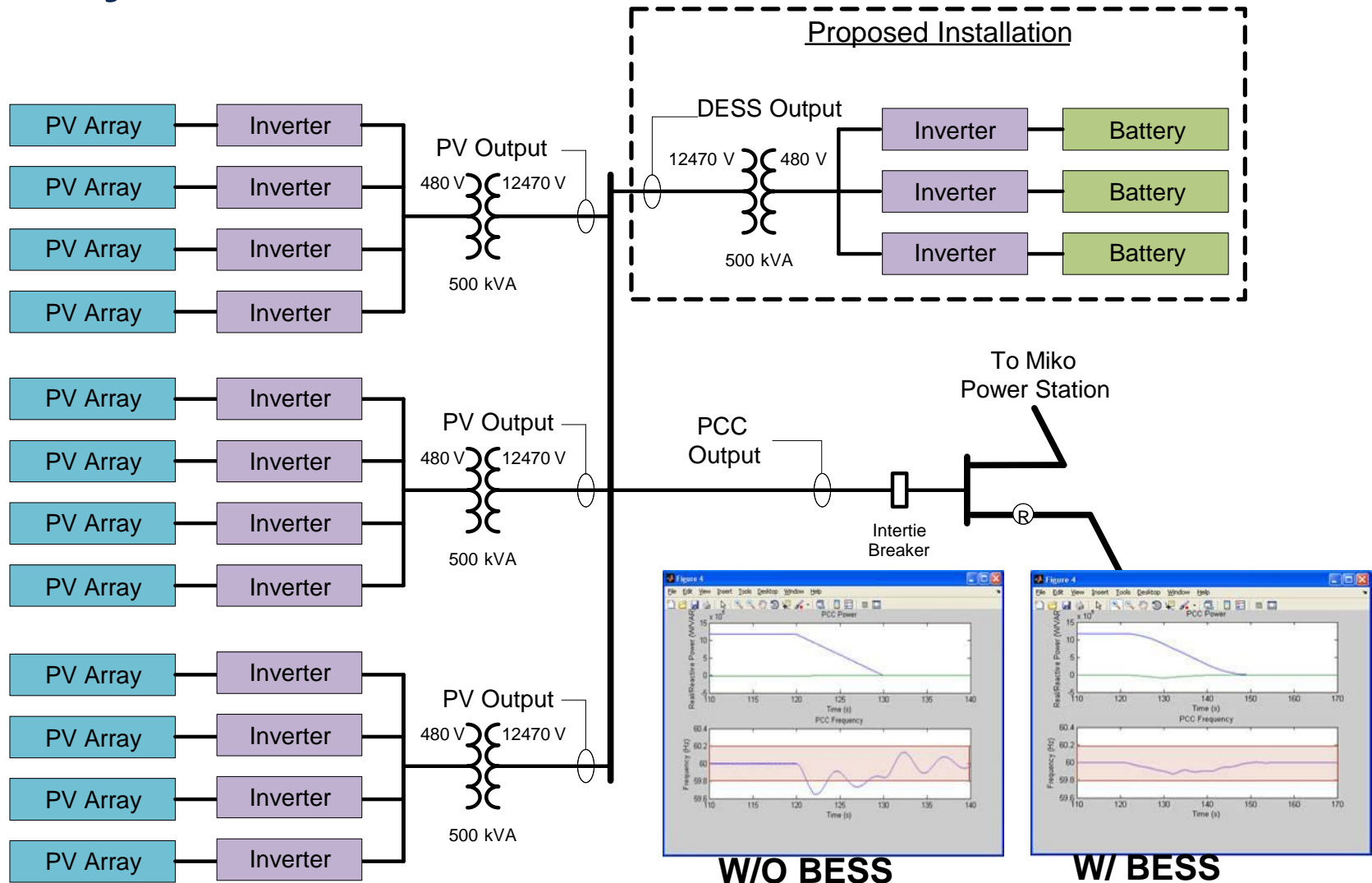
and

None

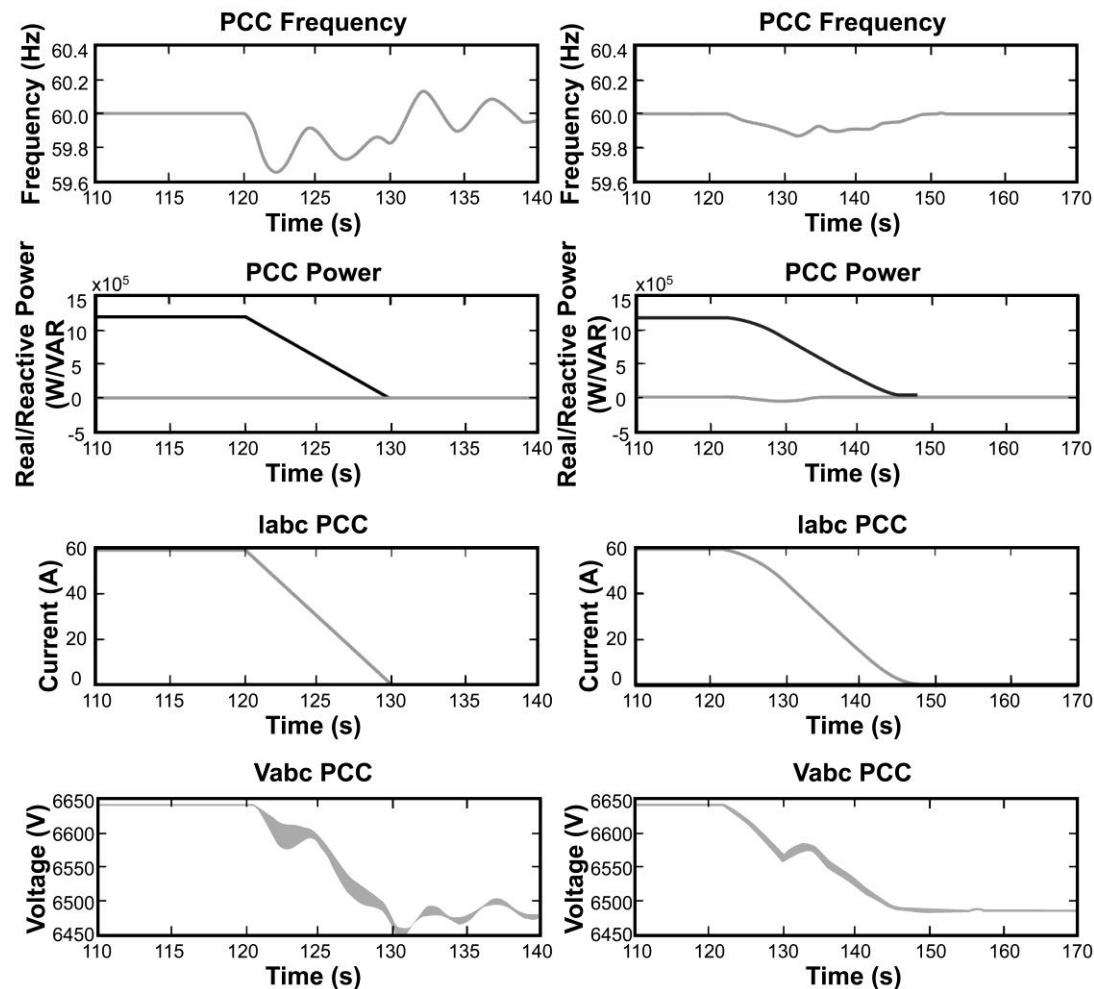
How Energy Storage Smooths PV



Lanai Grid Energy Storage Control Project



Frequency Response to ramp-rate control



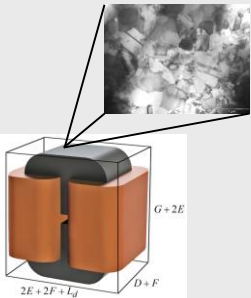
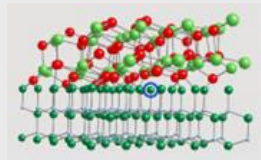
Lanai Battery

- Castle and Cooke selected Xtreme Power
- Battery system size: 1.125 MW; 500 kWh storage capacity



Energy Storage Power Electronics Program

Materials R&D



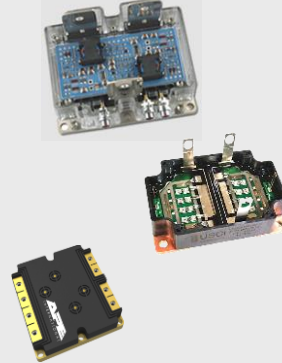
- Gate Oxide R&D
- Advanced Magnetics

Devices



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

Power Modules



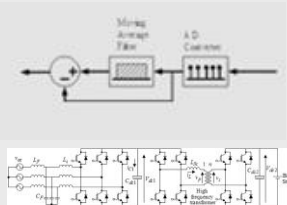
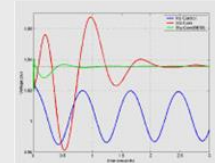
- SiC High Temp/density Power Module
- HV SiC JFET Module
- HV, HT Reworkable SiC half-bridge modules

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



Stanley Atcitty (Stan), Ph.D.

**Distinguish Member of Technical Staff
Energy Storage Technology and Systems Dept.
Sandia National Laboratories**

Phone: 505-284-2701

Email: satcitt@sandia.gov