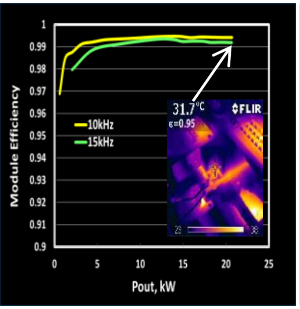
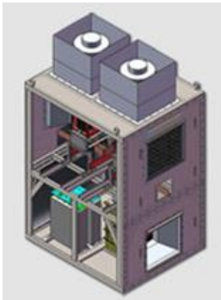
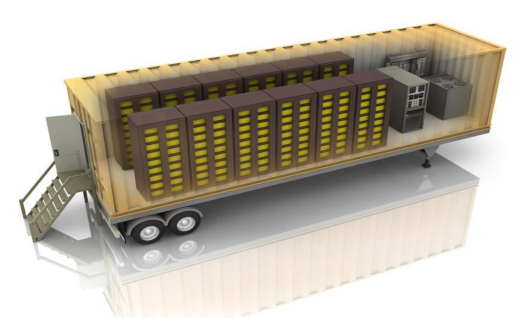
SAND2016-5880PE

DOE OE Energy Storage Power Electronics Program







Stan Atcitty

Energy Storage Technology and Systems Department 06111

Sandia National Laboratories

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Exceptional service in the national interest

U.S. DEPARTMENT OF ENERGY

NNSA

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- National Laboratory Policy Council
- Energy Council
- Credit Review Board
- Cyber Council
- Nuclear Security Council
- Jobs Council
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- Assistant Secretary for Energy Efficiency and Renewable Energy
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- Indian Energy Policy and Programs
- Office of Technology Transitions[1]

Office of the Under Secretary for Management & Performance

Vacant
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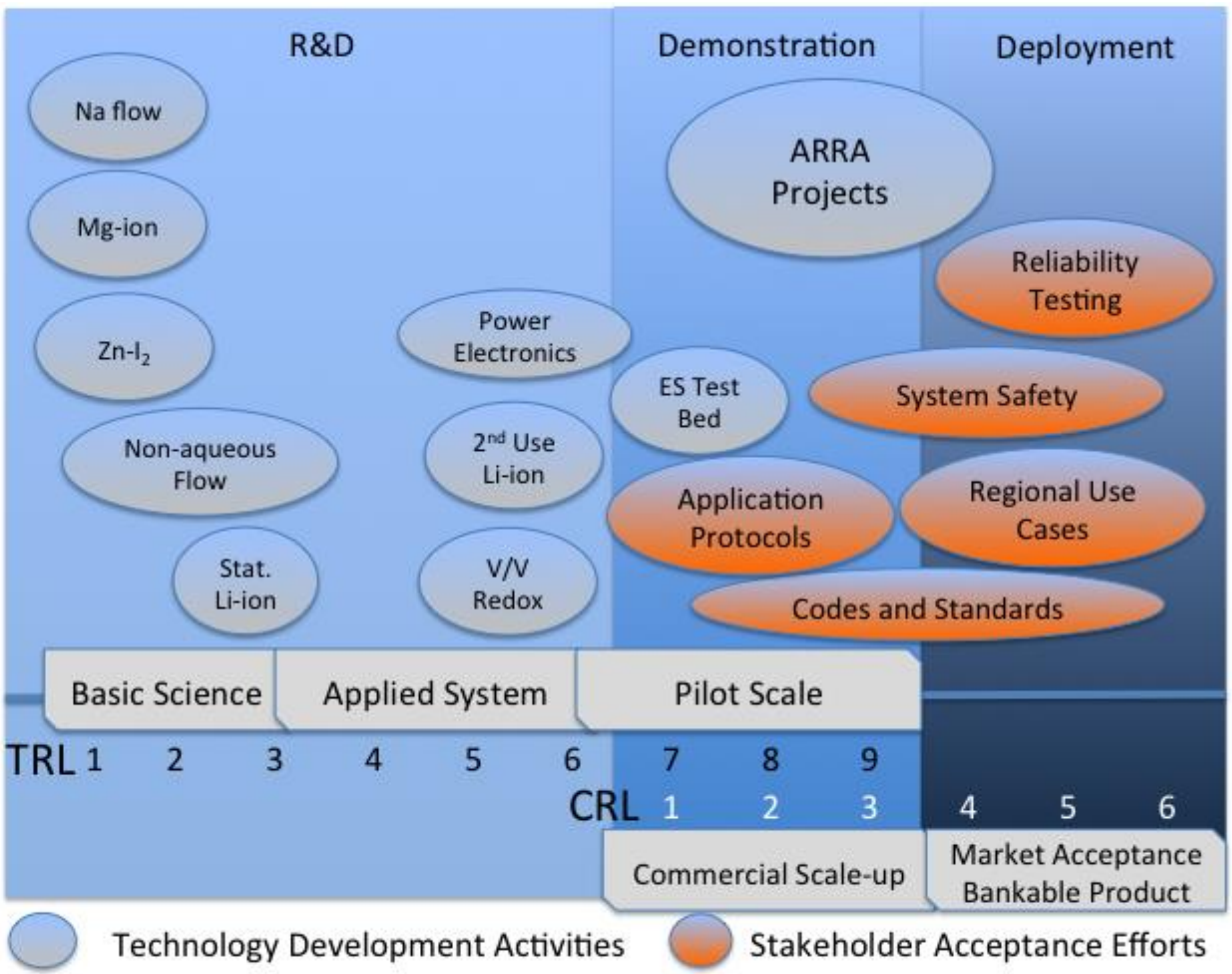
- U.S. Energy Information Administration
- Advanced Research Projects Agency - Energy
- Energy Policy & Systems Analysis
- Loan Programs Office
- Bonneville Power Administration
- Southwestern Power Administration
- Southeastern Power Administration
- Western Area Power Administration

[1] The director of the Office of Technology Transitions also serves as DOE's Technology Transfer Coordinator who reports to the Secretary of Energy

27 Jan 2016

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

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Traditional Grid

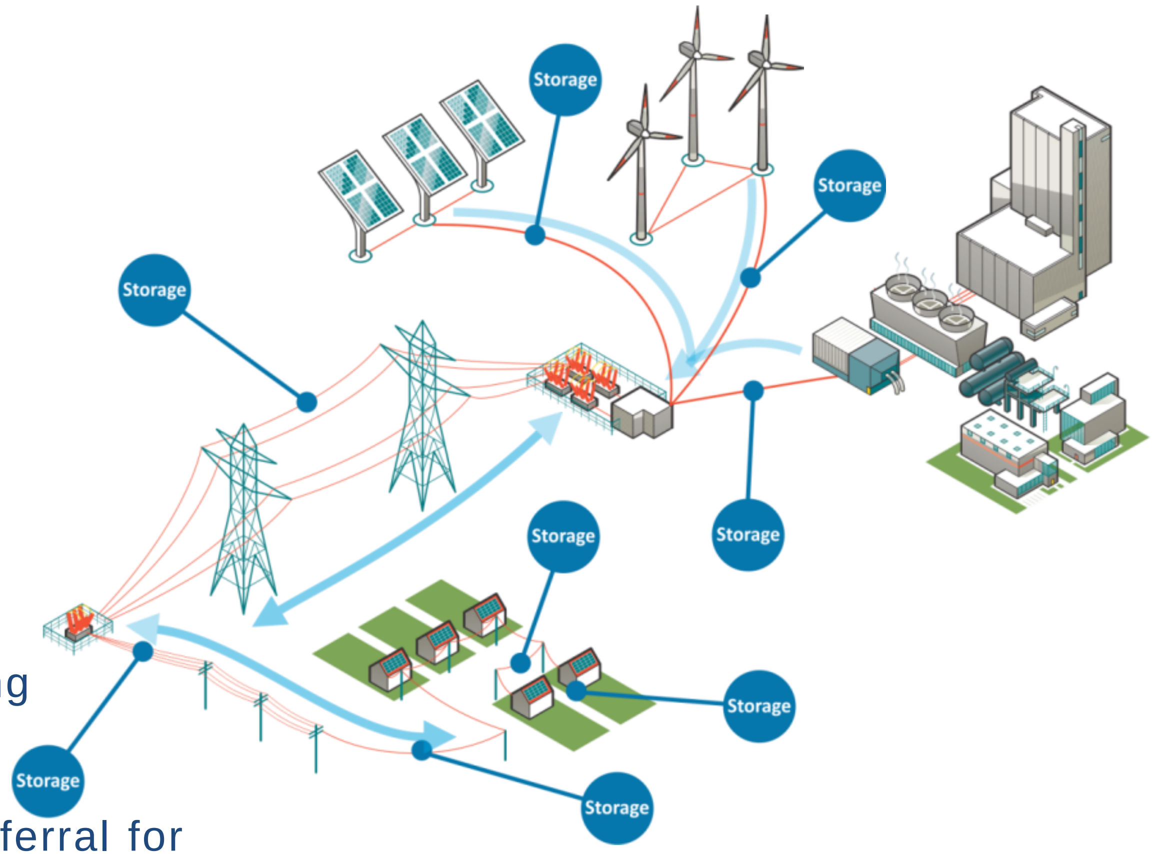
- One way flow
- Little/no renewable energy

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

Sandia National Laboratories

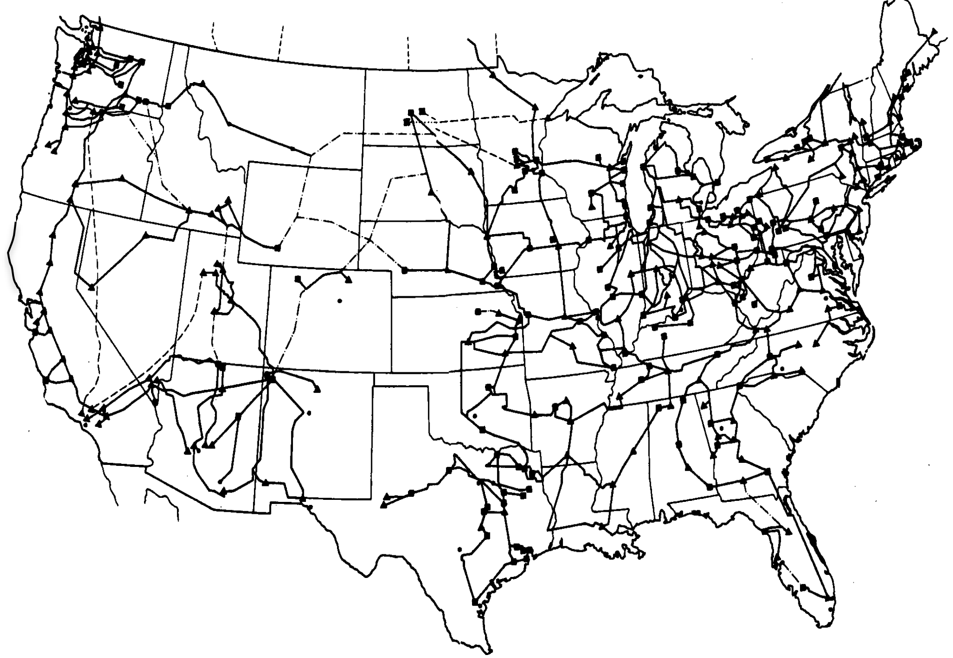
Common AC voltages

Transmission { 765kV, 500kV, 345kV, 230kV

Sub-Transmission { 69kV, 30kV

Distribution { 15kV, 4kV, 2kV, 600V, 480V, 240V, 120V

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



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

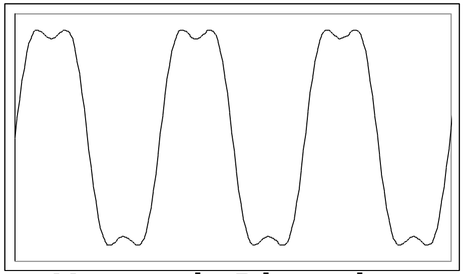
Source: http://www.globalsecurity.org/eye/blackout_2003.htm

~50M people effected

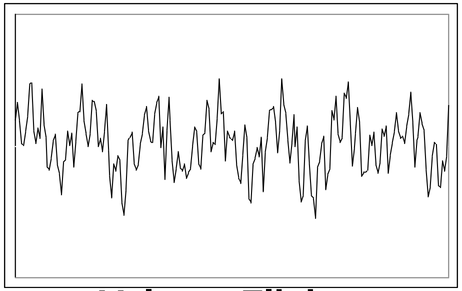
~6Billion in financial losses

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

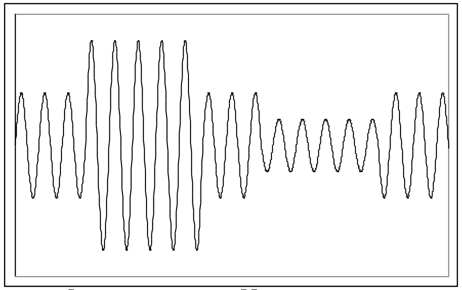
Other Electric Utility Challenges



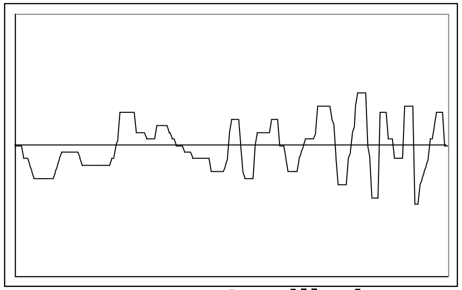
Harmonic Distortion



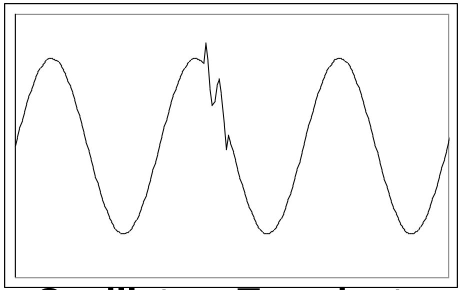
Voltage Flickers



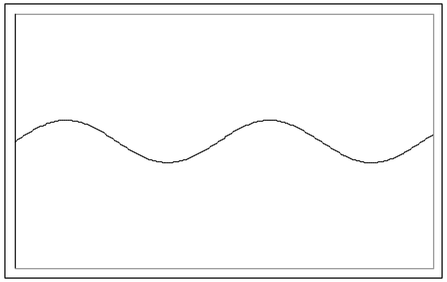
Voltage Swells & Sags



Frequency Oscillations



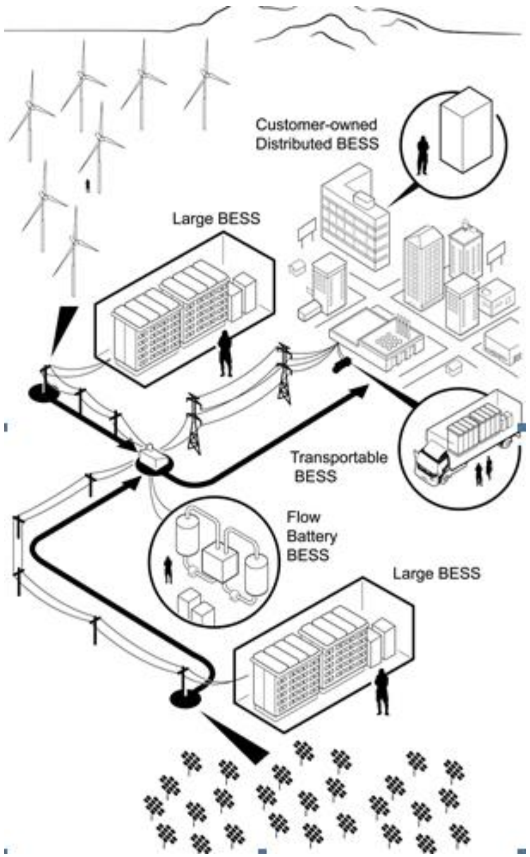
Oscillatory Transients



Subsynchronous Resonance

Energy Storage Rationale

- Transmission capacity limitations – curtailment of renewable sources during peak energy production
- Next generation grid (i.e. Smart Grids) – complex distributed controls of multiple sources and loads
- Increase penetration of variable energy sources (i.e. PV and Wind energy) –State renewable portfolio standards
- Bidirectional flow of energy from distributed energy resources
- Transmission deferrals combined with load growth

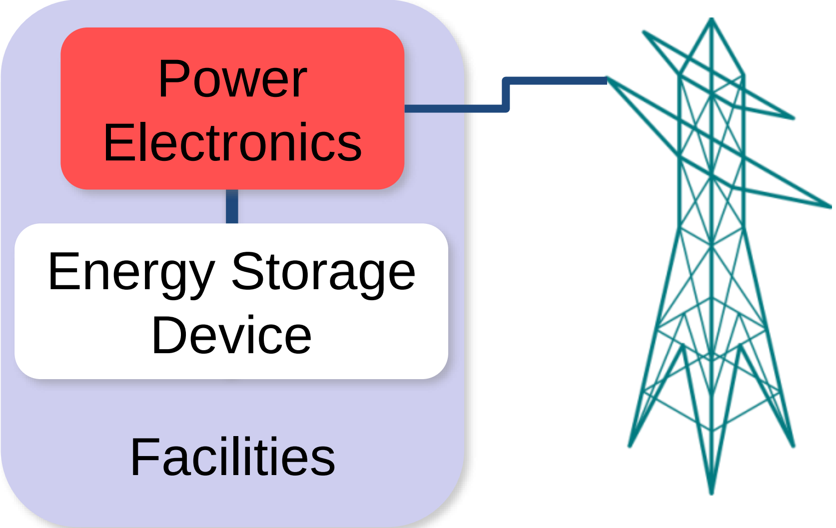


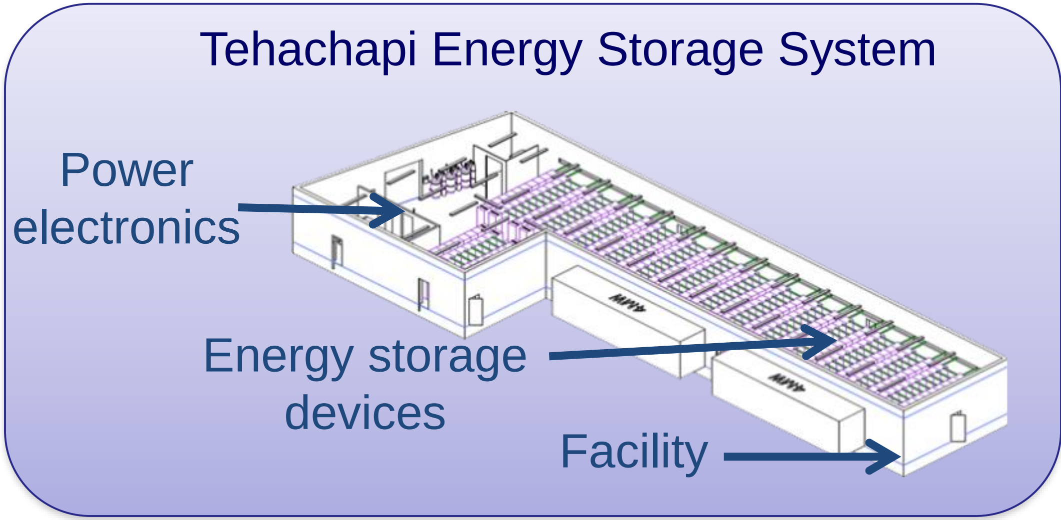
Source: Power Electronics for Renewable and Distributed Energy Systems: A Sourcebook of Topologies, Control and Integration

Energy Storage System Configuration

Energy Storage Systems contain three major components:

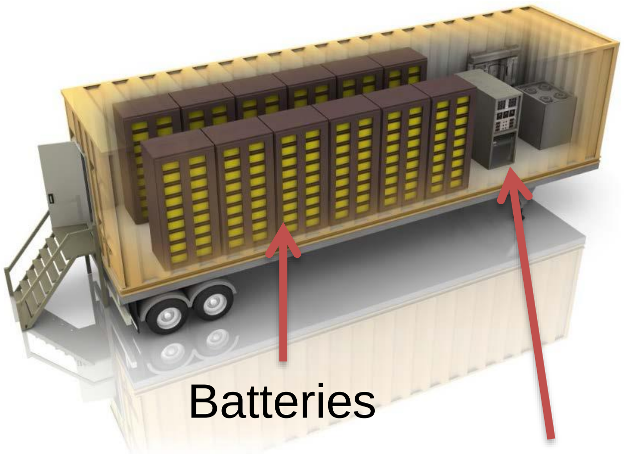
- Energy storage device
  - Where energy is held until needed
  - Ex: chemical/electrolyte (used in battery), flywheel, etc.
  - ~25-40% of overall costs
- Power electronics
  - Ensures proper and safe charge and discharge of storage device and can provide grid support
  - ~20-25% of overall costs
- 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

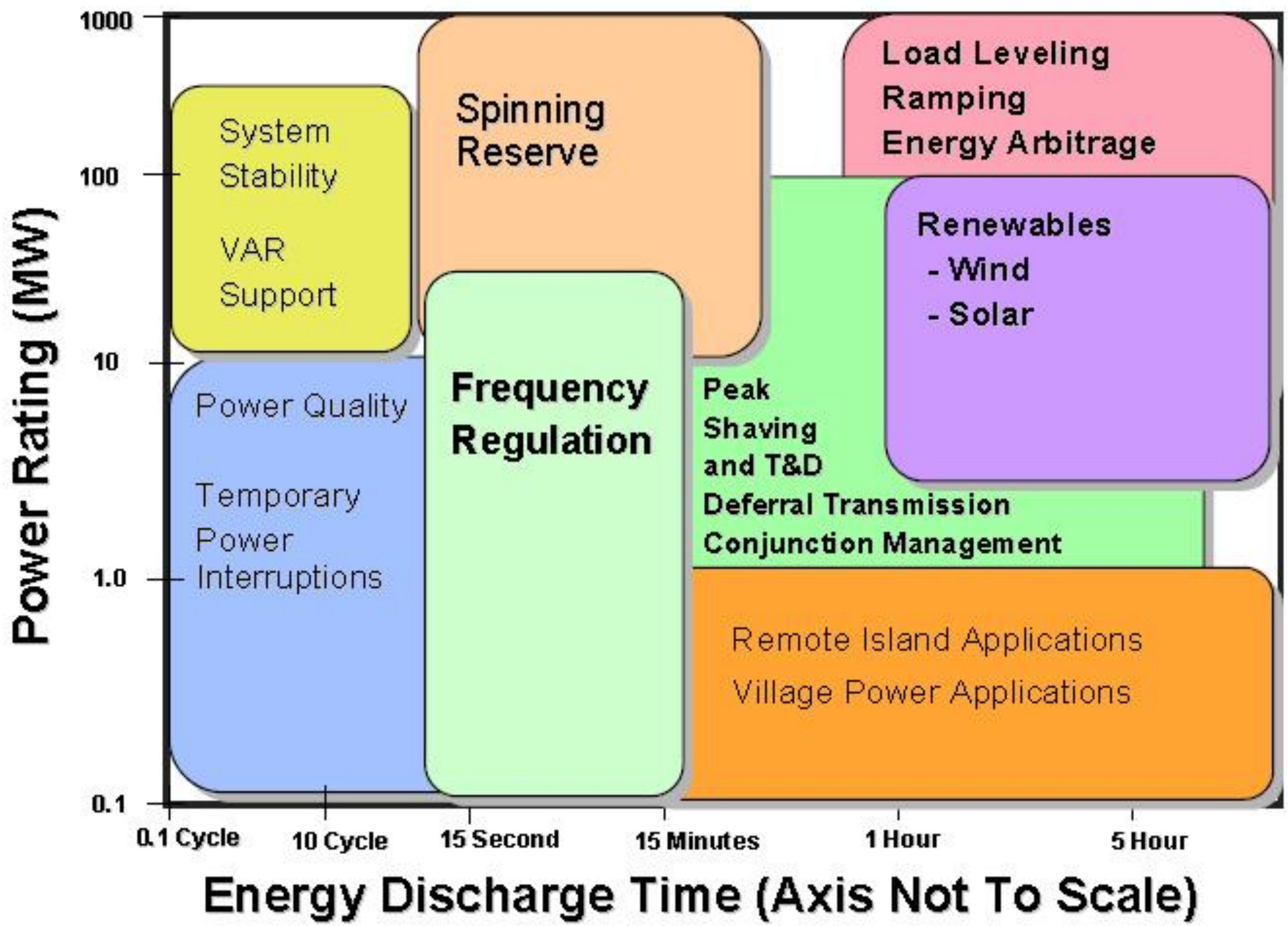
Transportable Energy Storage Systems



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

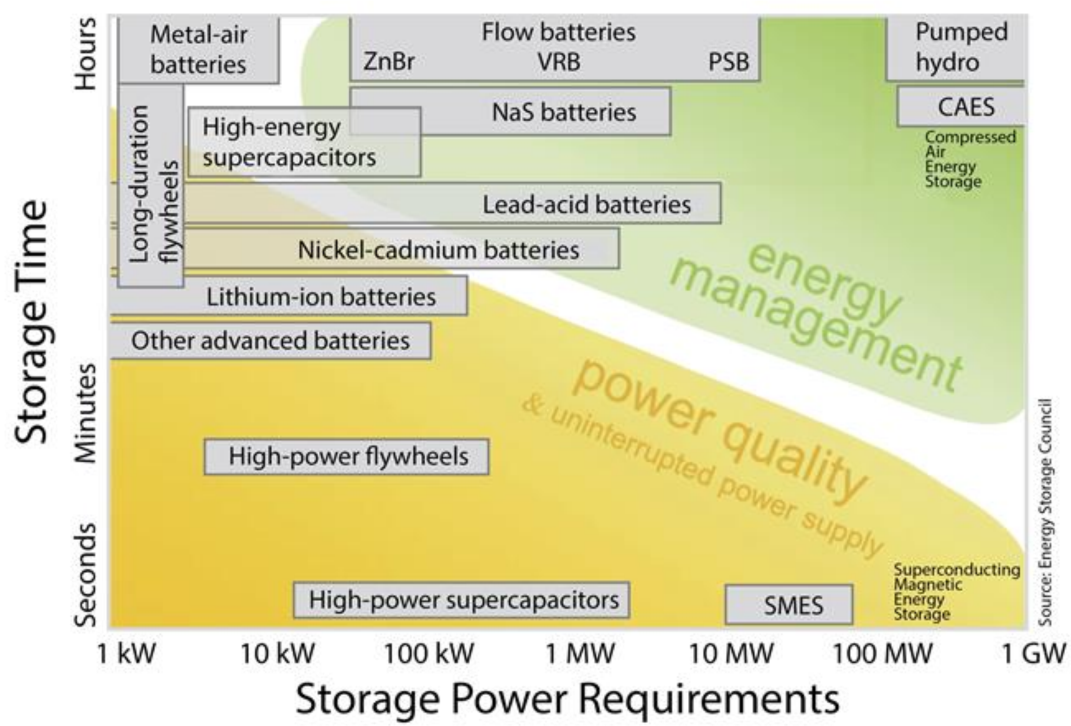
- Pumped Hydro
- Compressed Air Energy Storage (CAES)
- Batteries
  - Sodium Sulfur (NaS)
  - Flow Batteries
  - Lead Acid
  - Advanced Lead Carbon
  - Lithium Ion
- Flywheels
- SMES
- Electrochemical Capacitors

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

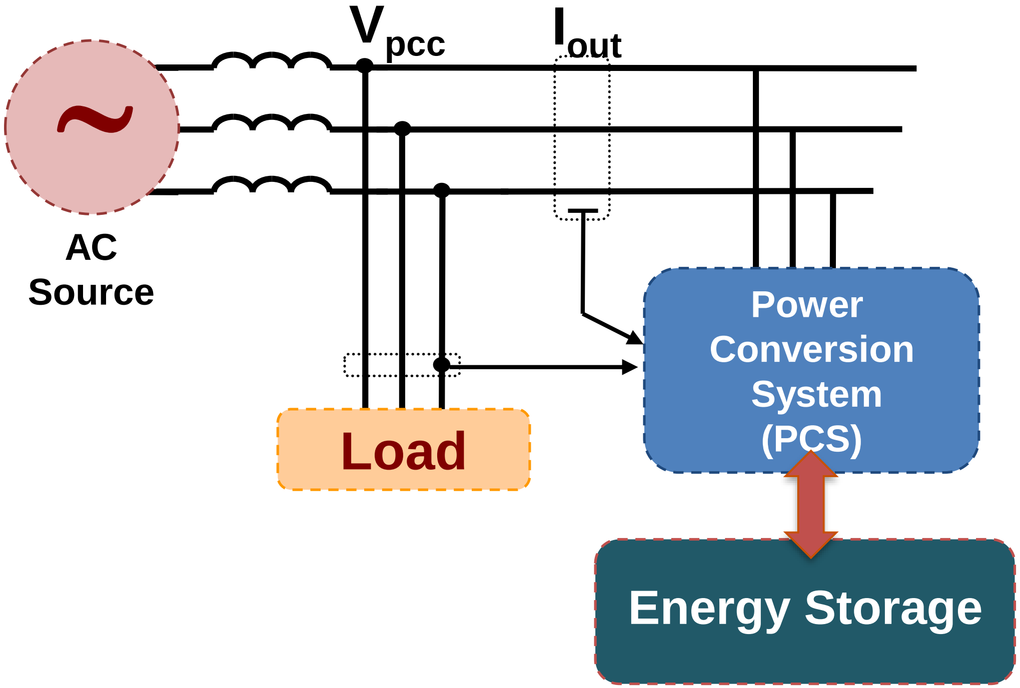


Energy Storage Classification

- **Electromechanical**
  - Flywheels
- **Electrochemical**
  - Batteries
    - Ph-acid
    - NiCd
    - NaS
    - NiMh
    - Li-ion
    - Metal Air
    - Advanced Pb Carbon
  - Flow Batteries
    - ZnBr
    - Vanadium Redox
  - Electrochemical Capacitors
- **Electromagnetic**
  - Superconducting Magnetic
- **Thermodynamic**
  - Compresses Air

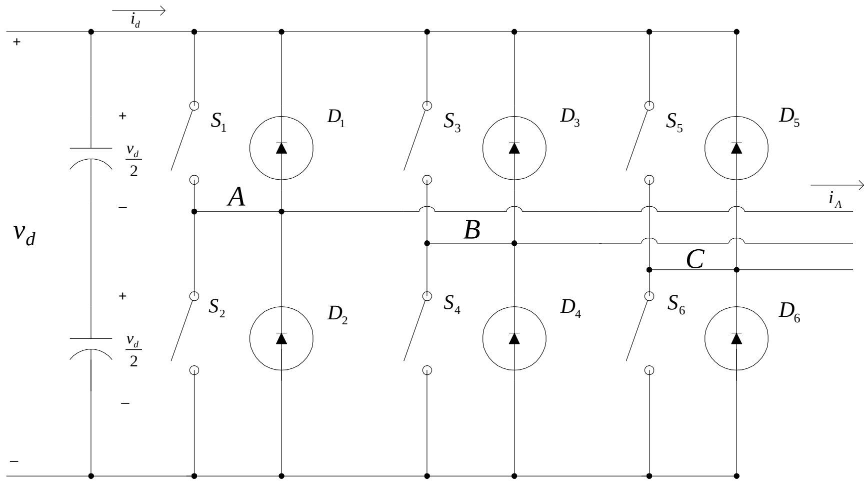
Why is DOE OE/Sandia interested in power electronics?

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

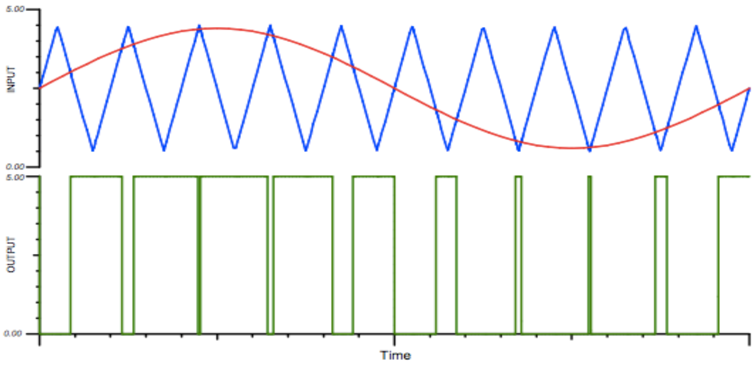


The PCS is a key component of the energy storage system. It can represent 20 to 60% of the total system cost.

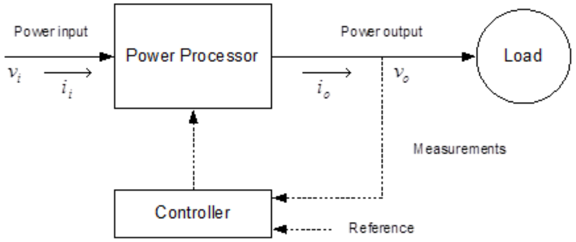
Power Conversion System



Three-phase inverter



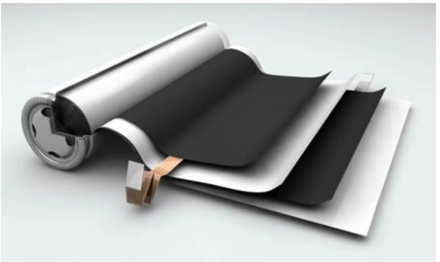
Construction of a PWM signal (output of a comparator (green) with a sawtooth wave (blue) and a reference signal (red)



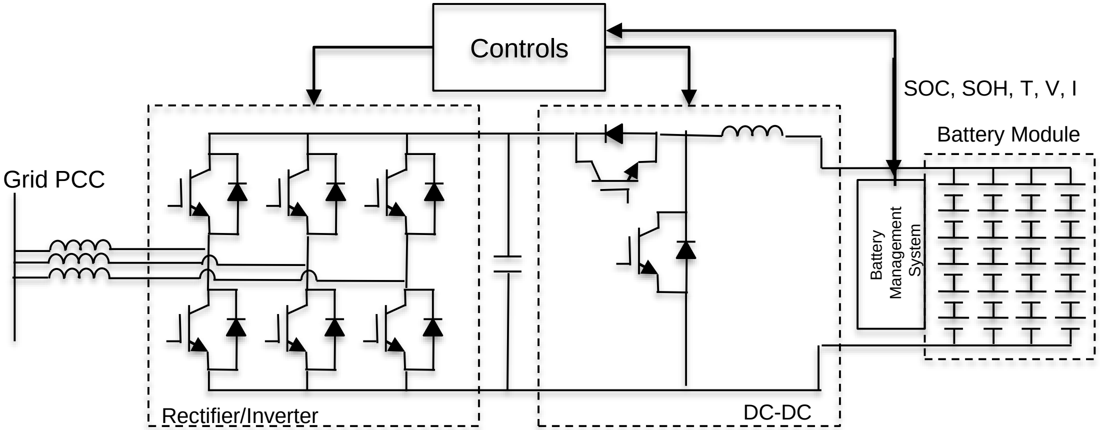
- Single-Phase and Three-phase DC/AC inverter topologies
- Heart of the system – semiconductor switches
- PWM signal is constructed. The sawtooth wave and reference signal are compared in a controller shown in the block diagram. The resulting PWM signal is sent to the Power Processor

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

Flywheel Energy Storage System

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

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

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

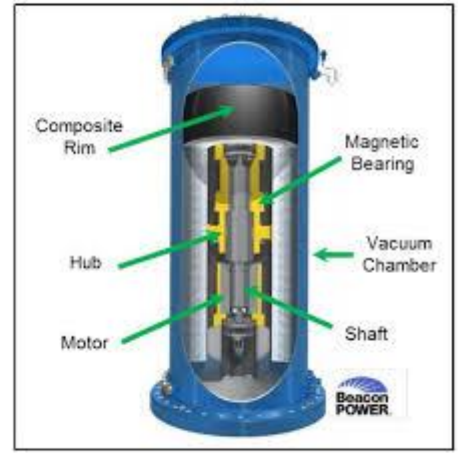
$\omega = angular\ velocity$

$I = moment\ of\ inertia$

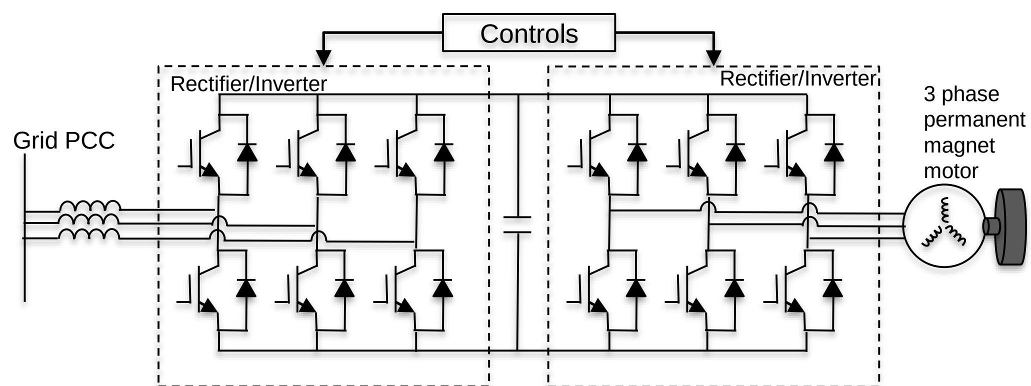
$m = mass$

$r = radius$

- 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

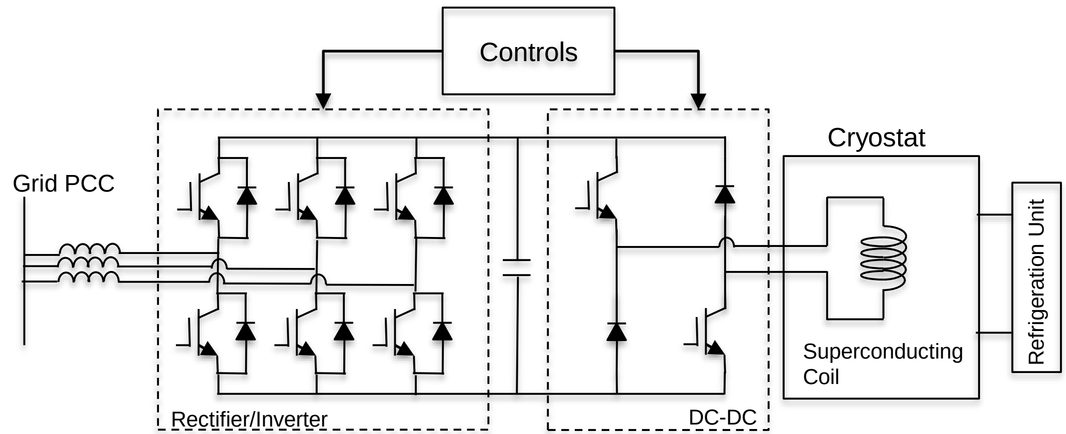


Typical Electrical Configuration of a FWES

Superconducting Magnetic Energy Storage System

- 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

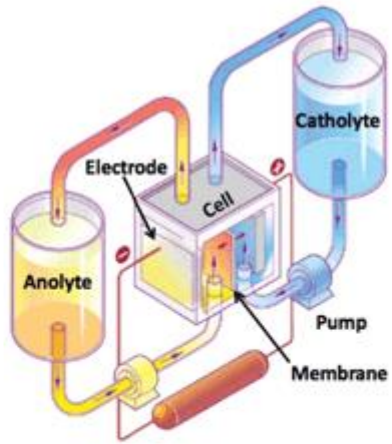
$$E = \frac{1}{2} \cdot L \cdot I^2$$



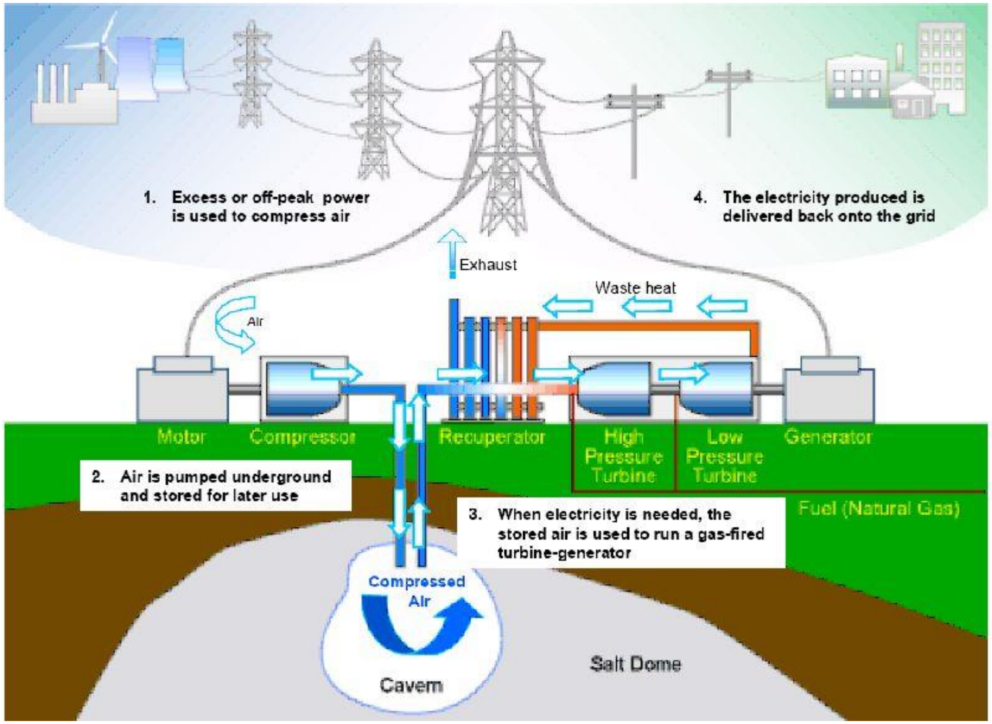
Typical Electrical Configuration of a SMES

Other Energy Storage Technologies

Electrochemical Capacitor Energy Storage



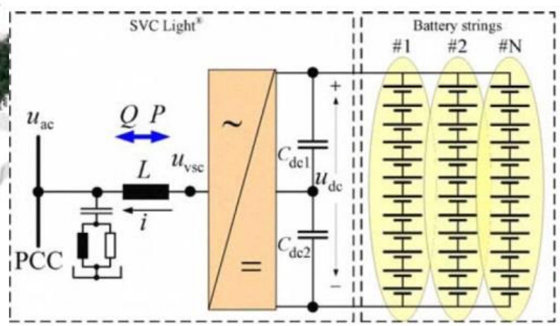
Flow Battery Energy Storage



Compressed Air Energy Storage

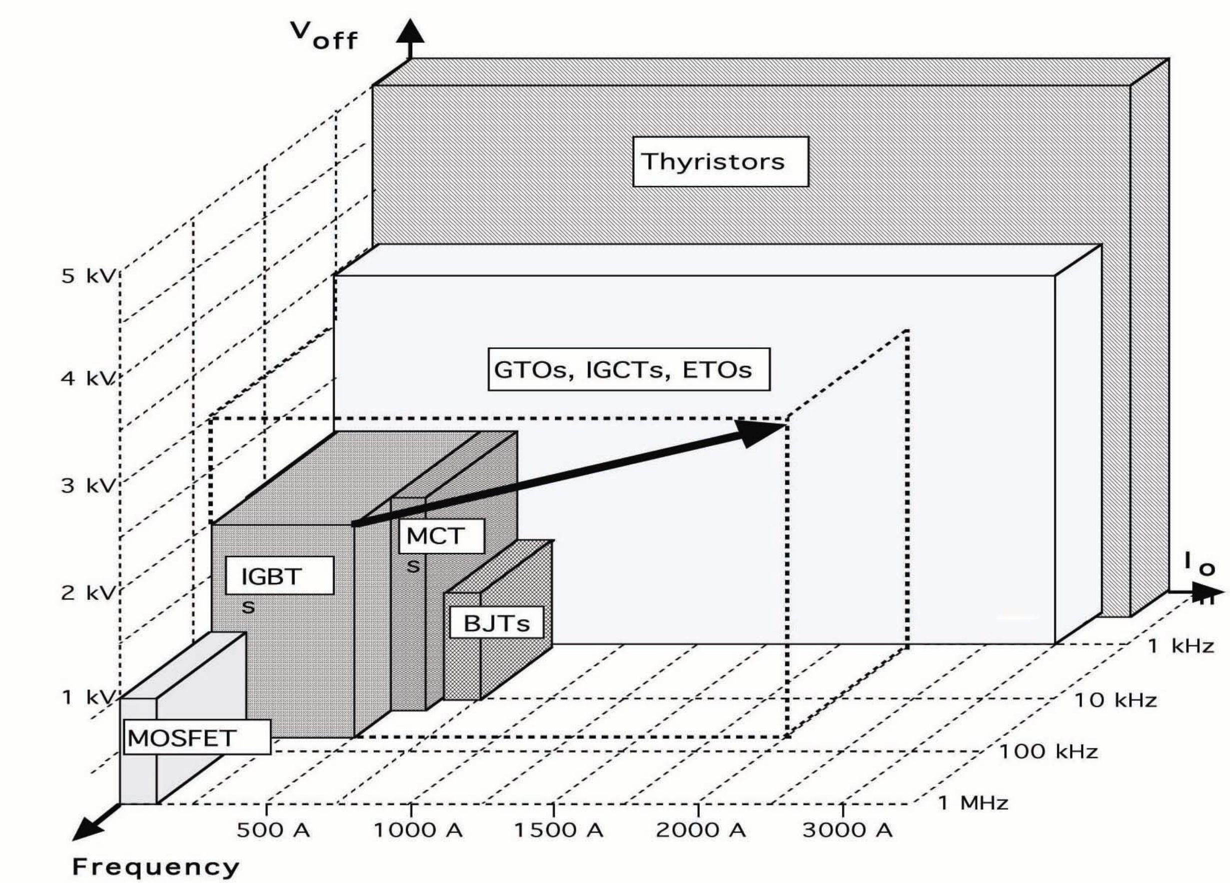
Examples of Large Energy Storage Demonstrations

- 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



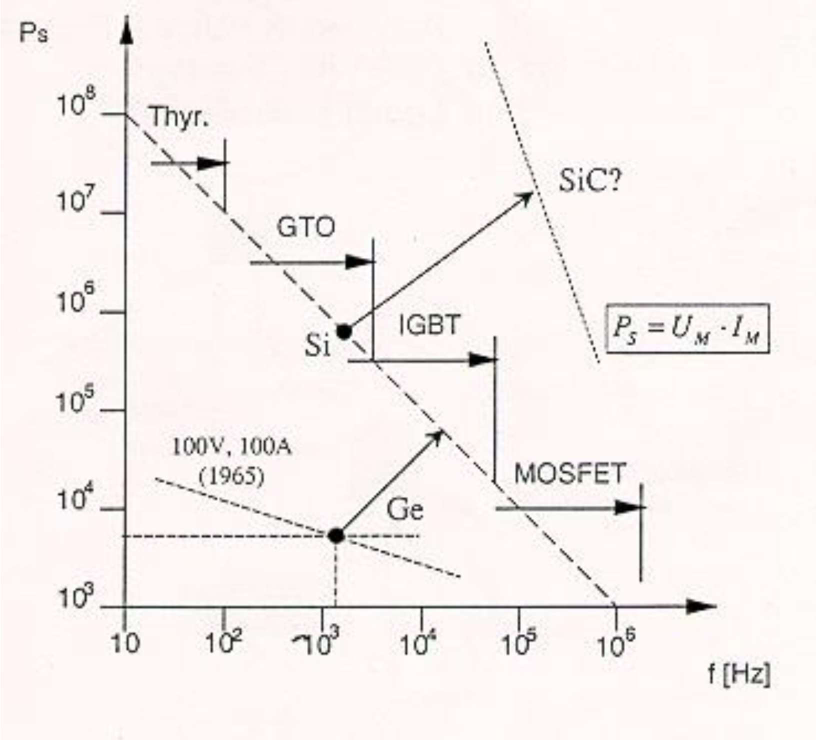
Trends:

- **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

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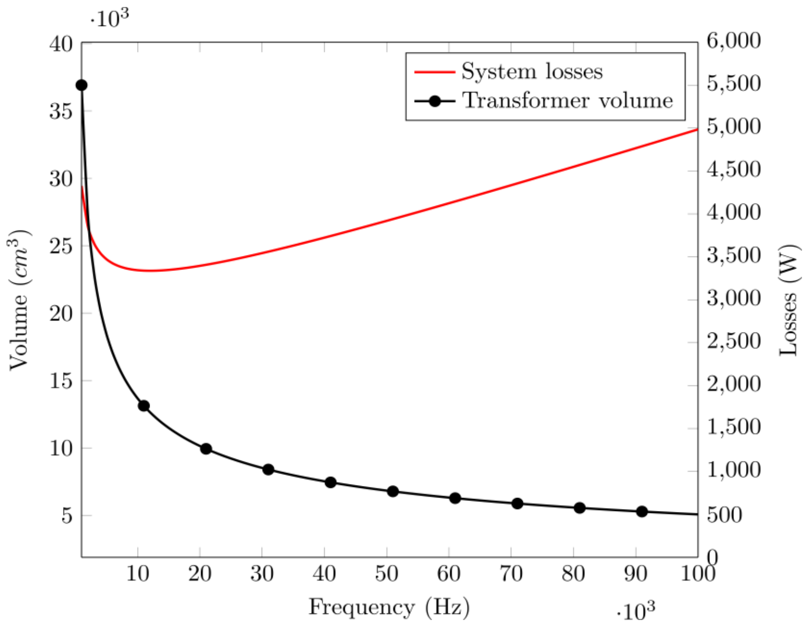
100 kHz Ferrite Transformer
8 kW – 328 grams (0.72 lbs)

60 Hz Si-Steel Transformer
7.5 kVA – 150 lbs

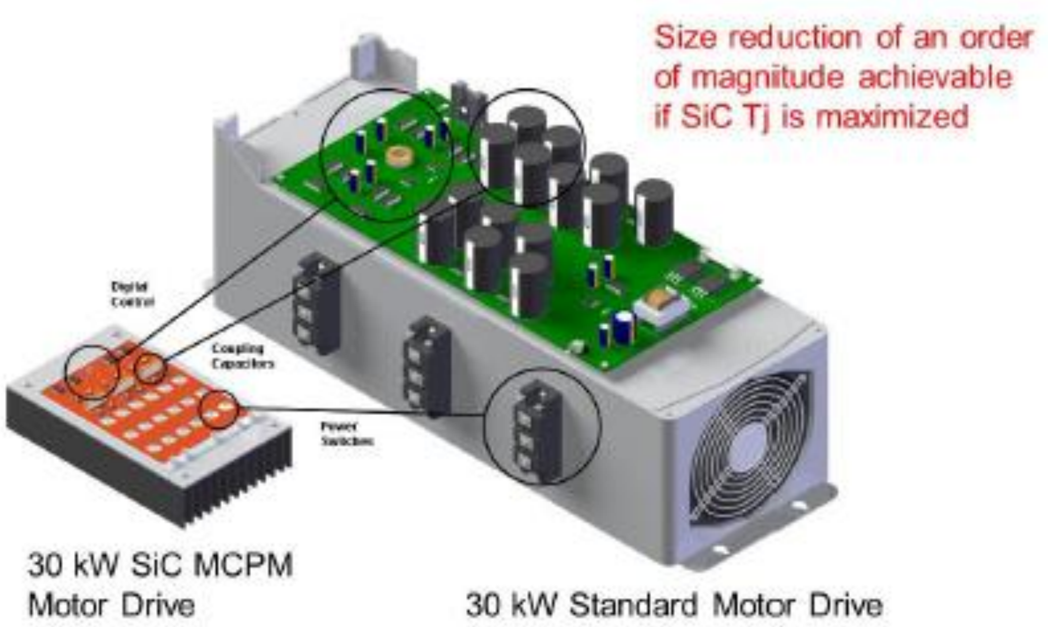
Source: Wolfspeed



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



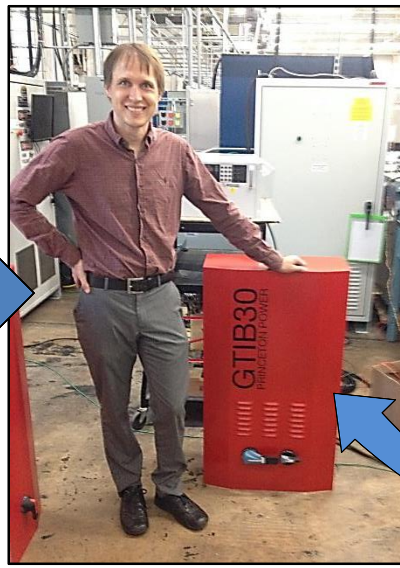
Source: Wolfspeed

Example: 30kW SiC Inverter

Sandia National Laboratories

PRINCETON POWER SYSTEMS
Clean Power Made Simple™

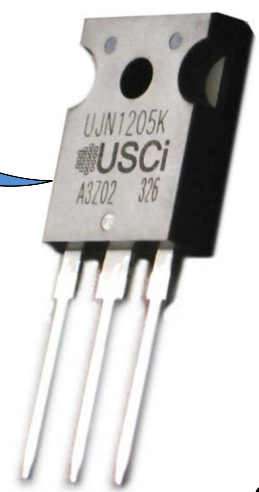
30kW Bidirectional Inverters



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



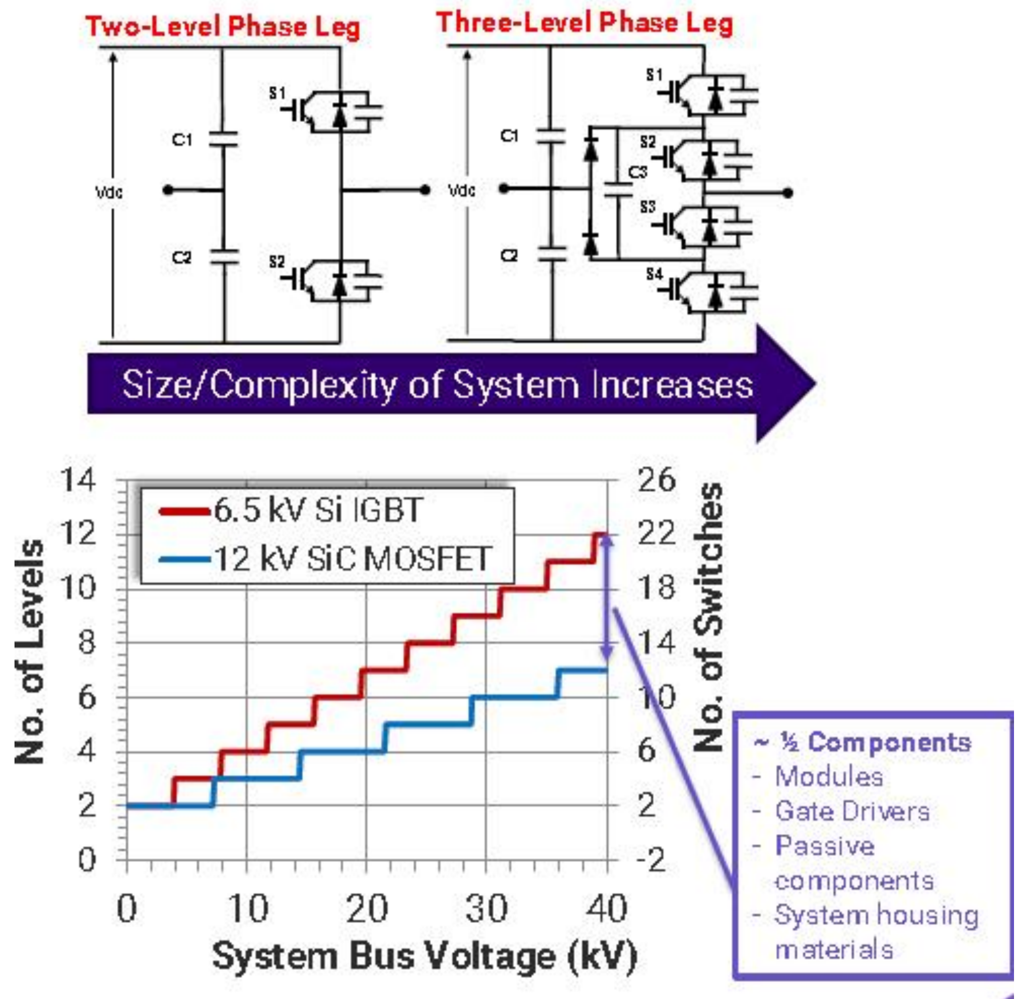
UJN1208K TO-247

Parameter	Value	Unit
$R_{DS(on)}$	80	mΩ
V_{DS}	1200	V
T_{max}	175	°C

Source: USCi

High voltage SiC – reduce system, size and complexity

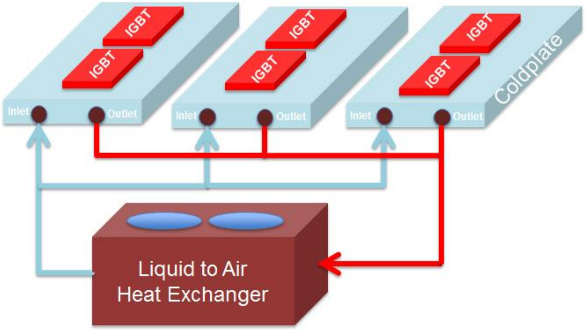
- To increase system bus voltage, multi-level converter designs are typically used
- The number of power switches used in such systems can be reduced
- Fewer components – lower cost, higher efficiency, higher reliability



Source: Wolfspeed

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

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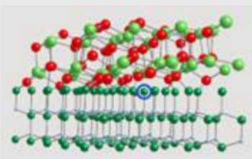
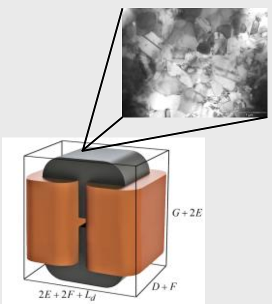
Energy Storage Power Electronics Program

Materials R&D



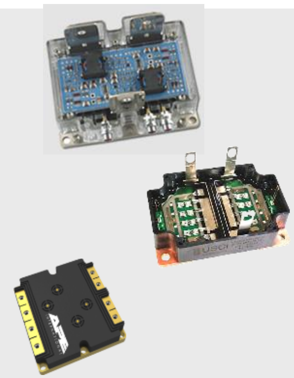


- Gate Oxide R&D
- Advanced Magnetics

Devices

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

Power Modules

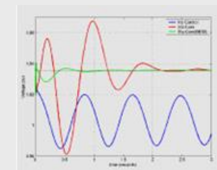


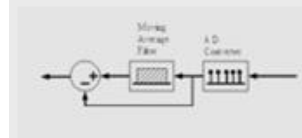
- SiC High Temp/density Power Module
- HV SiC JFET Module
- HV, HT Reworkable SiC half-bridge modules

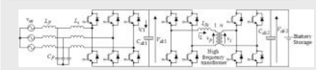
Power Conversion System

- 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

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