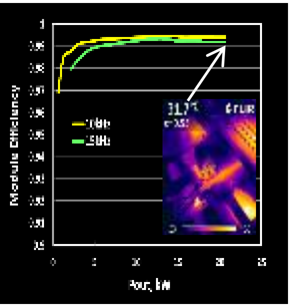

Sandia National Laboratories

Exceptional service in the national interest

SAND2018-1722C

Role of Power Electronics and Power Conversion Systems in Grid-Tied Energy Storage

Stan Atcitty

Energy Storage Technology and Systems Department 08811

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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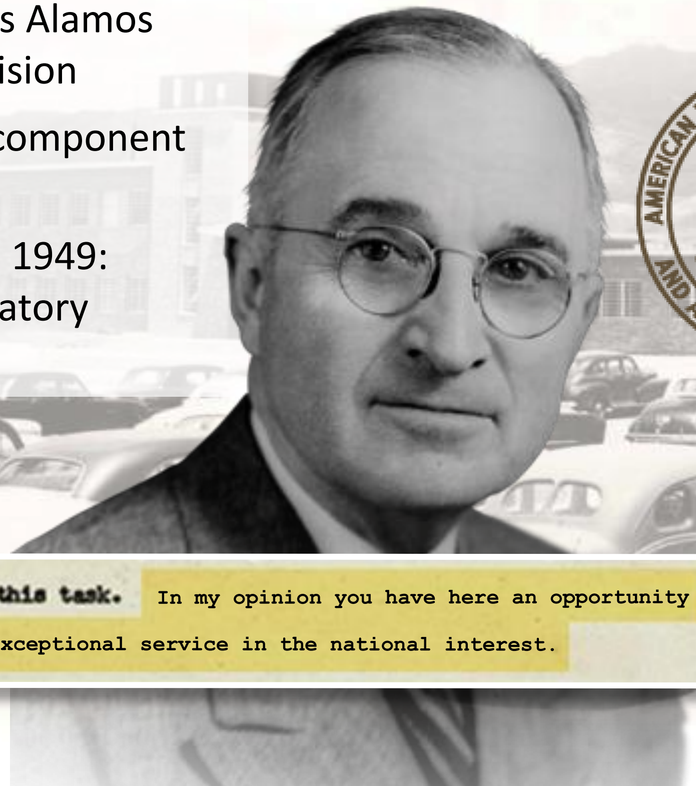
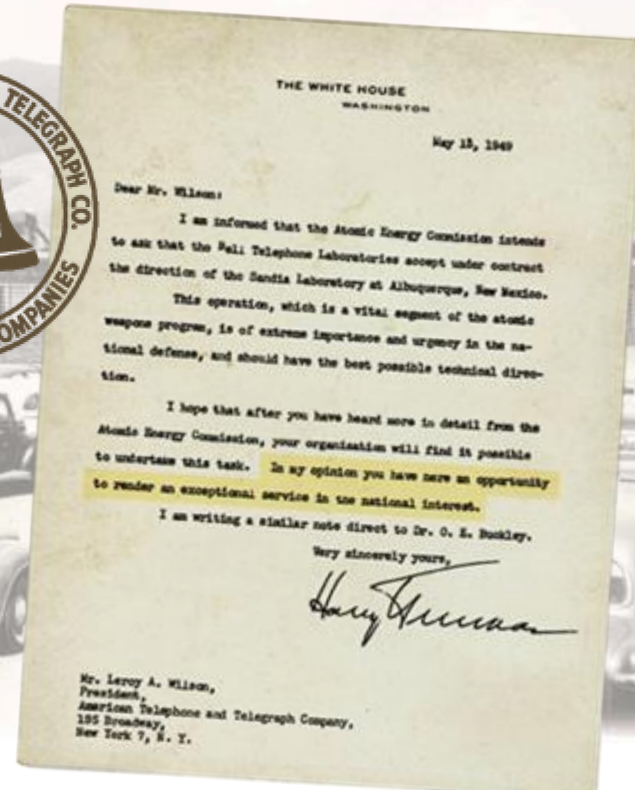
Sandia's History

Exceptional service in the national interest

- July 1945: Los Alamos creates Z Division
- Nonnuclear component engineering
- November 1, 1949: Sandia Laboratory established





THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico.

This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.

to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

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

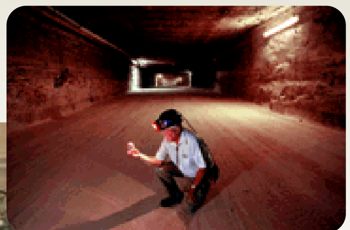
ARPAe, BES Chem Sciences, ASCR, CINT, Geo Bio Science, BES Material Science

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

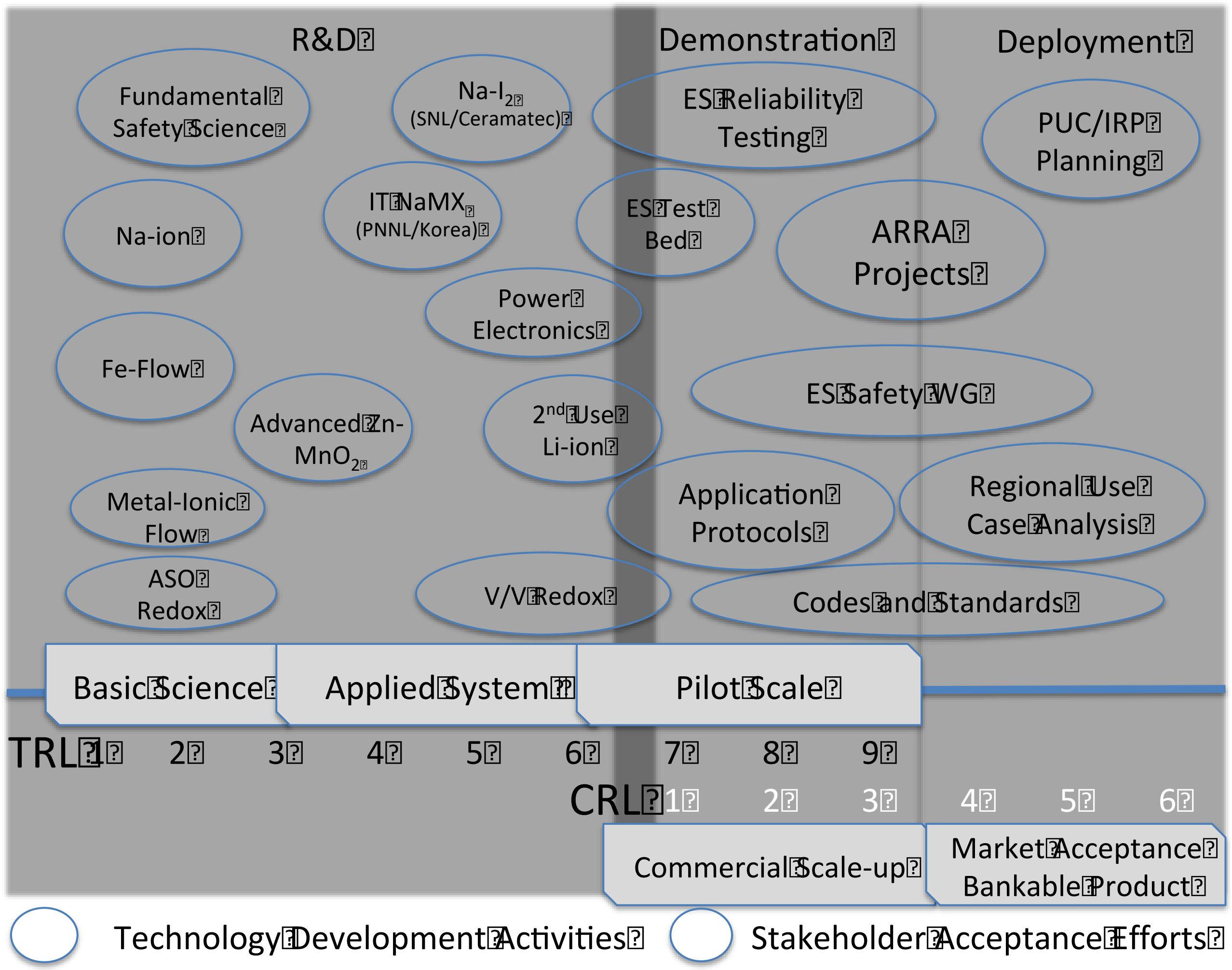
Vehicle Technologies, Biomass, Fuel Cells & Hydrogen Technology

DOE Office of Electricity Energy Storage Program

- The goal of the DOE 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 (OE).
- The Energy Storage Program is managed by Dr. Imre Gyuk.

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

DOE Grid Energy Storage Program



Grid Energy Storage program covers the entire technology development cycle, in partnership with universities, other labs, and companies

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

Traditional Grid

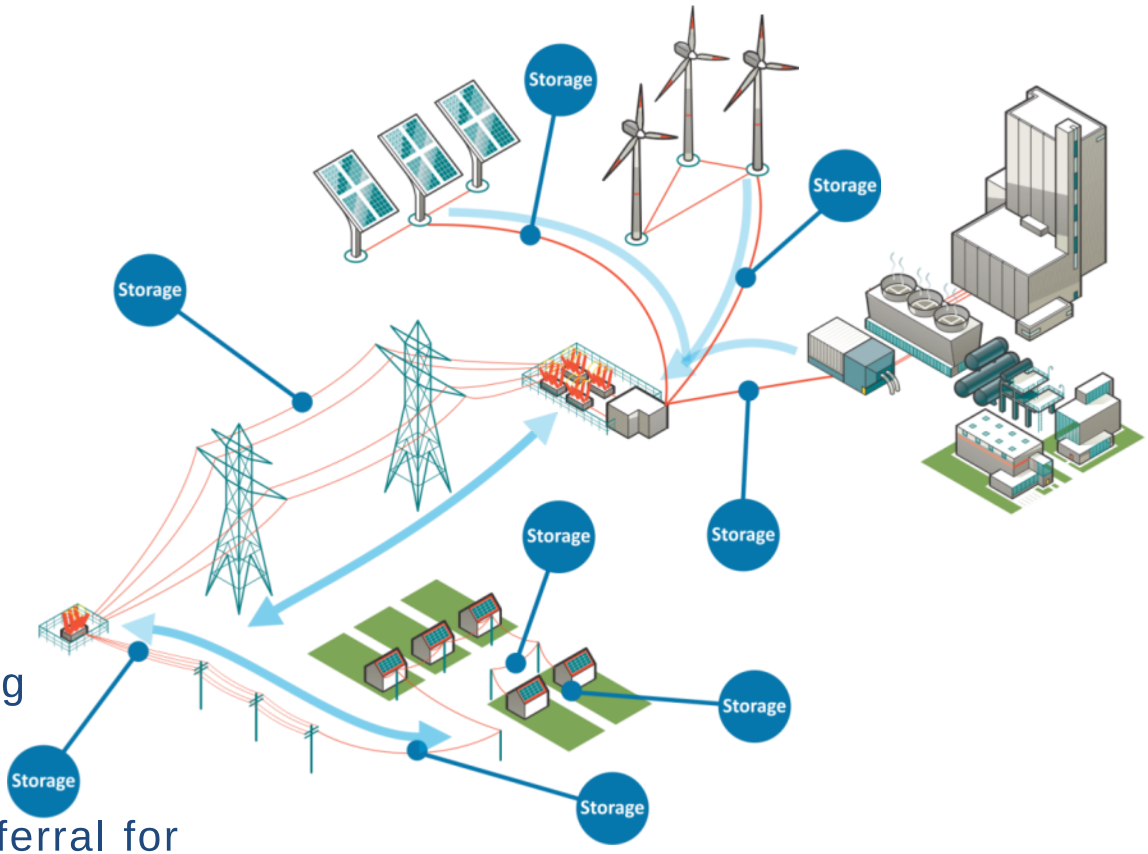
- One way flow
- Little/no renewable energy

Today's Grid

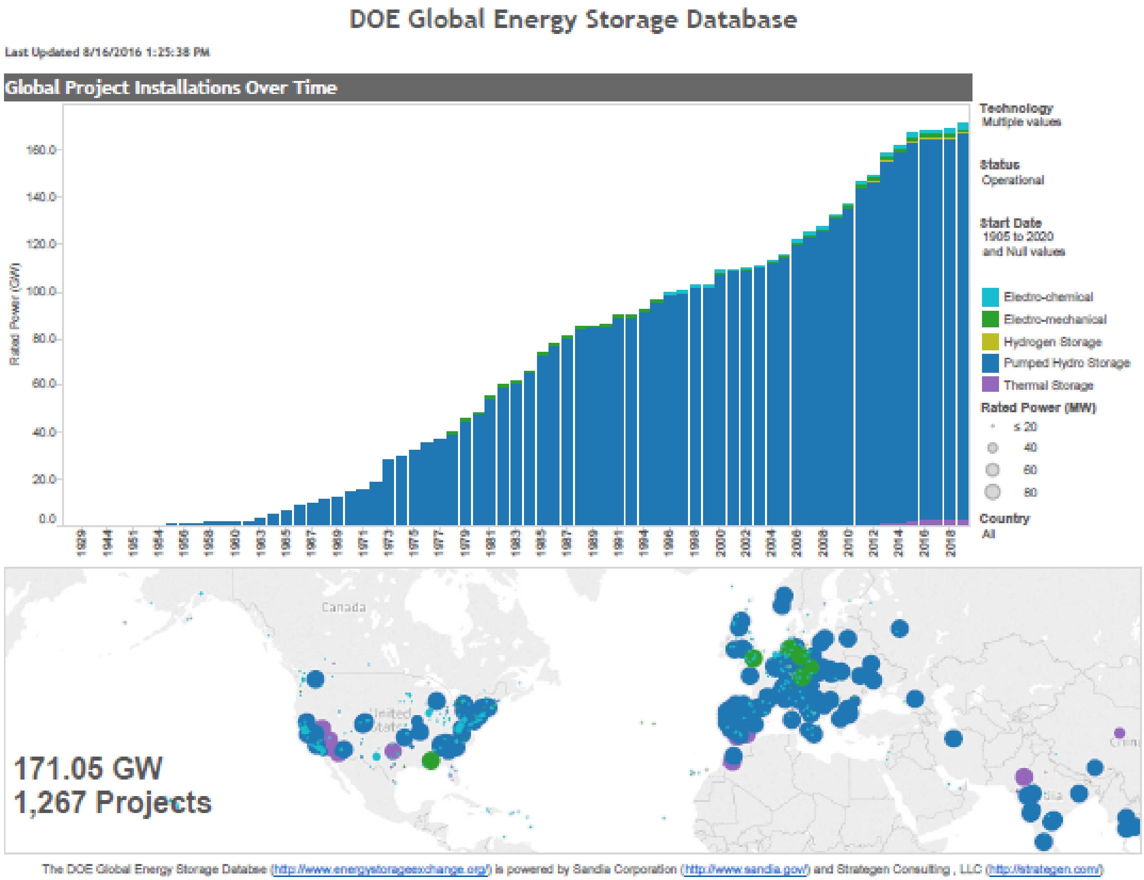
- Integration of grid-scale and distributed renewable generation beginning, but with limited penetration

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



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

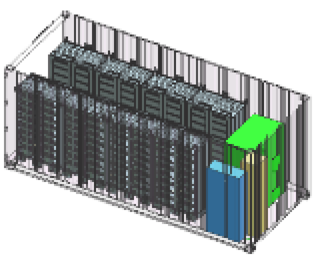
According to market research firm IHS, the energy storage market is set to grow to an annual installation size over 40 GW by 2022.

Elements of Energy Storage System

Sandia National Laboratories

Storage

- Cell
- Battery Management & Protection
- Racking



Integration

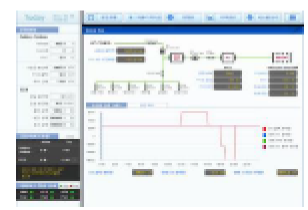
- Container / Housing
- Wiring
- Climate control

PCS

- Bi-directional Inverter
- Switchgear
- Transformer
- Skid

EMS

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



Cost Structure of Storage System in 2016

Storage
Racks+BMS

+

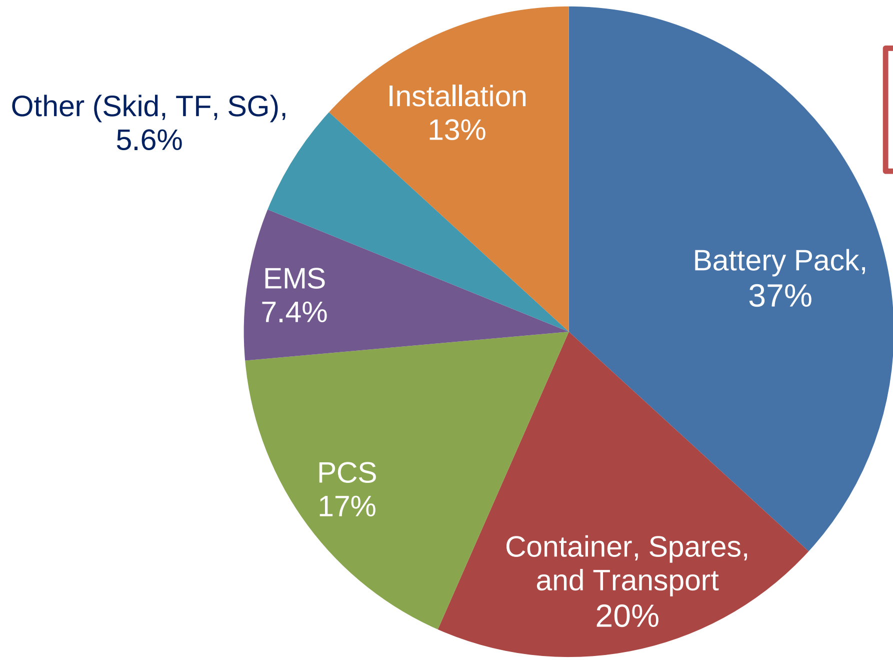
Product
Integration

+

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

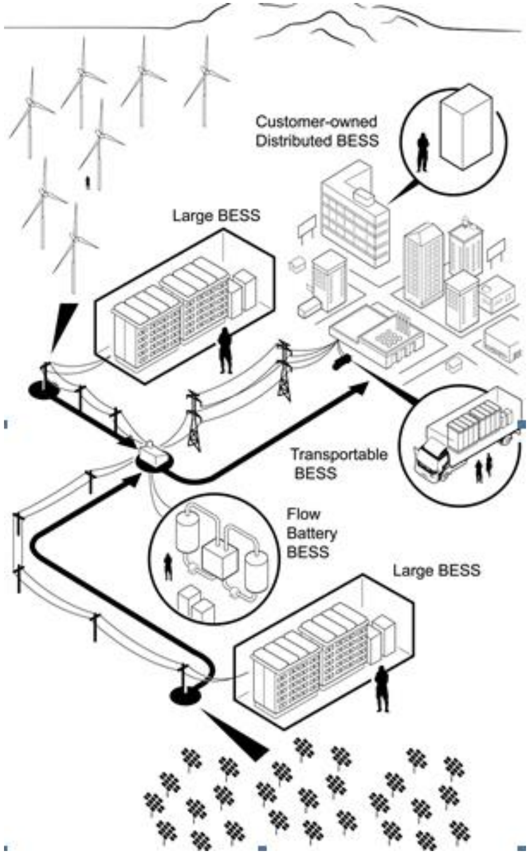
Data: Multiple industry sources

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



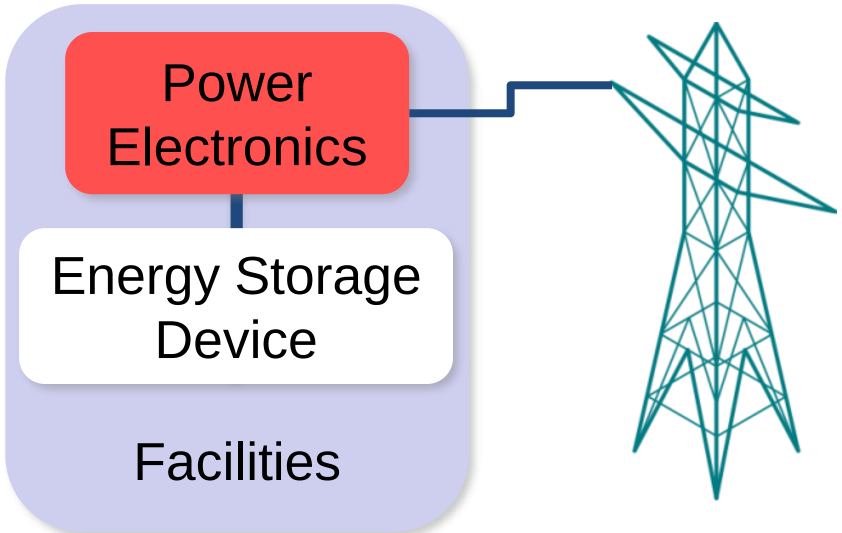
Source: Power Electronics for Renewable and Distributed Energy Systems: A Sourcebook of Topologies, Control and Integration

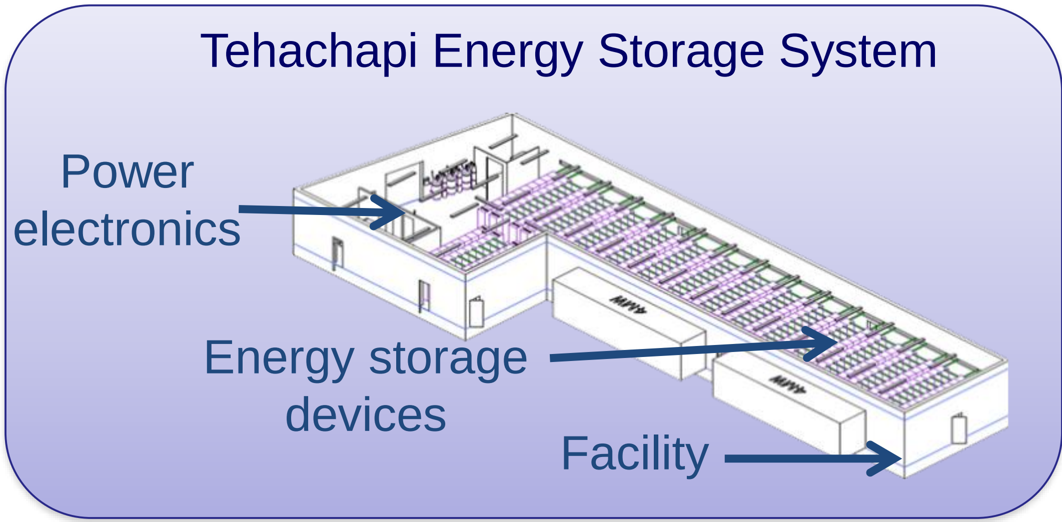
Energy Storage System Configuration

Energy Storage Systems contain three major components:

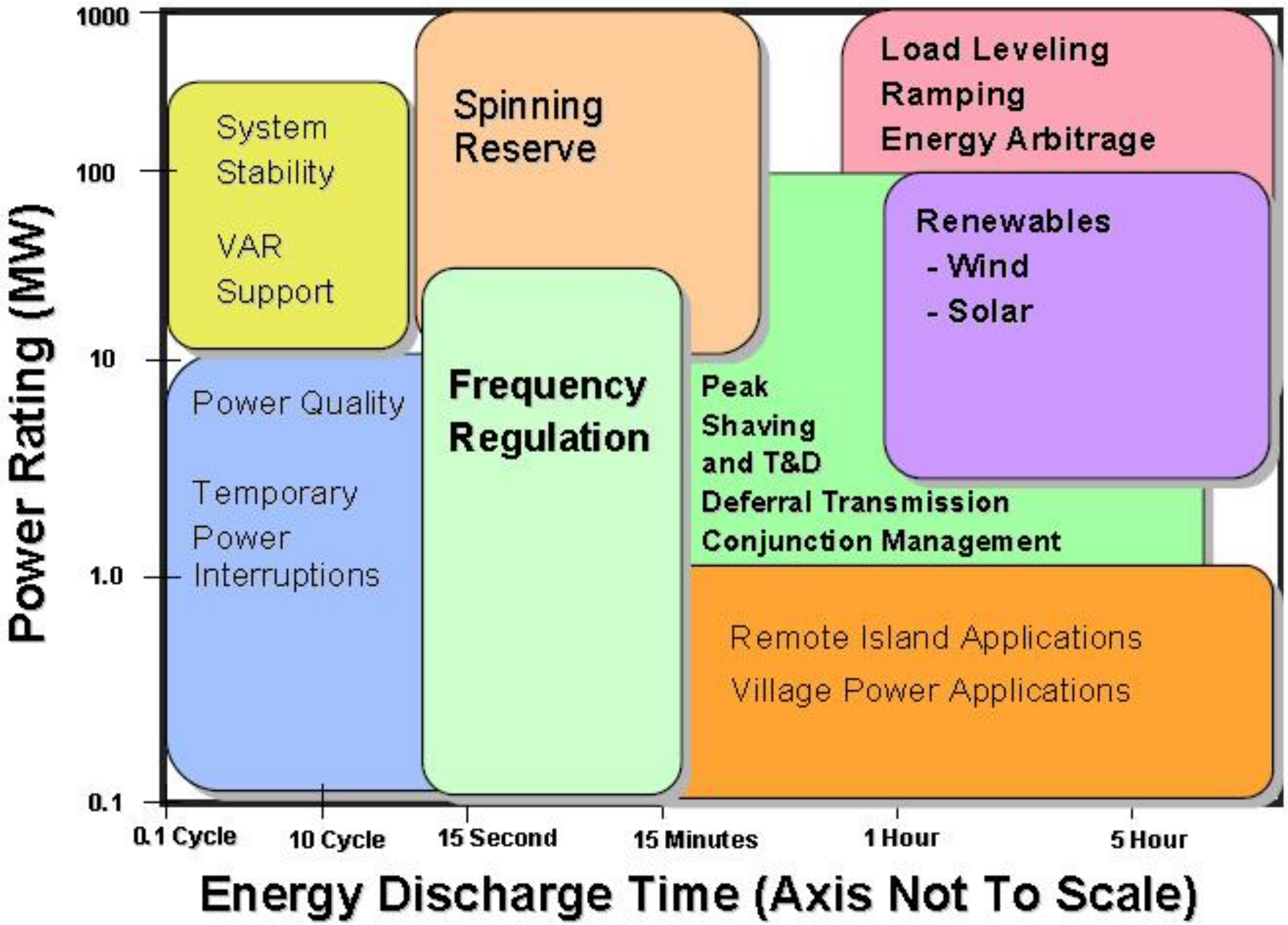
- Energy storage device
  - Where energy is held until needed
  - Ex: chemical/electrolyte (used in battery), flywheel, etc.
  - ~25-40% of overall costs
- Power electronics
  - Ensures proper and safe charge and discharge of storage device and can provide grid support
  - ~20-25% of overall costs
-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

Energy Storage Technologies

Energy

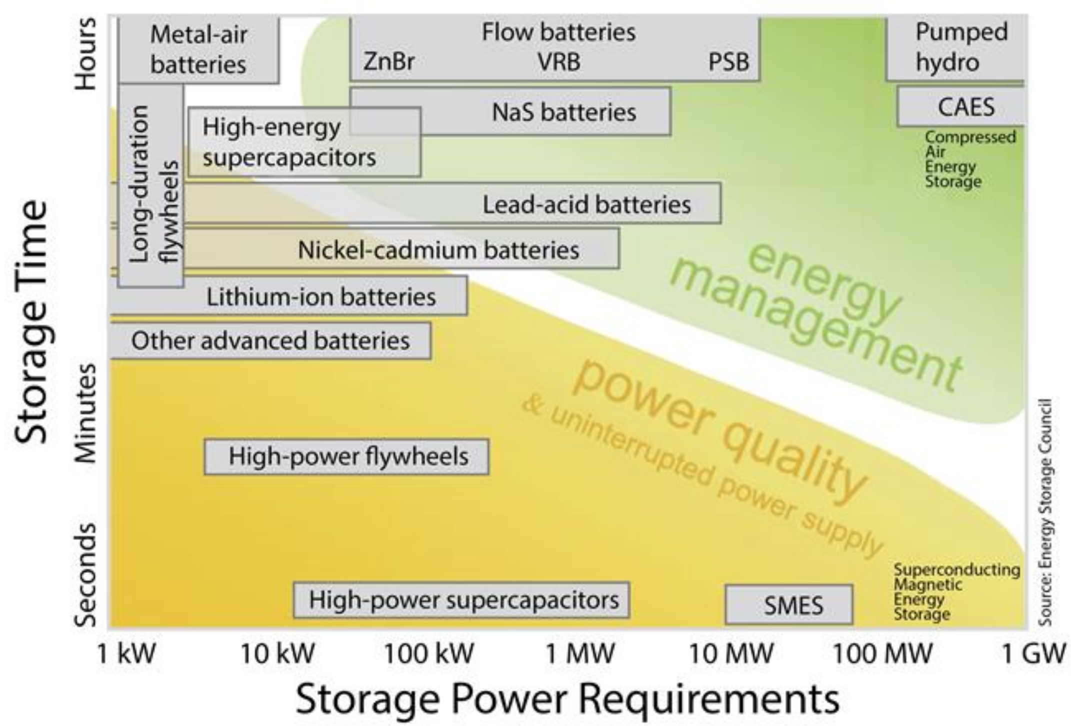
- Pumped Hydro
- Compressed Air Energy Storage (CAES)
- Batteries
  - Sodium Sulfur (NaS)
  - Flow Batteries
  - Lead Acid
  - Advanced Lead Carbon
  - Lithium Ion
- Flywheels
- Superconducting magnetic energy storage (SMES)
- Electrochemical Capacitors

Power

Two regimes, multiple technologies:

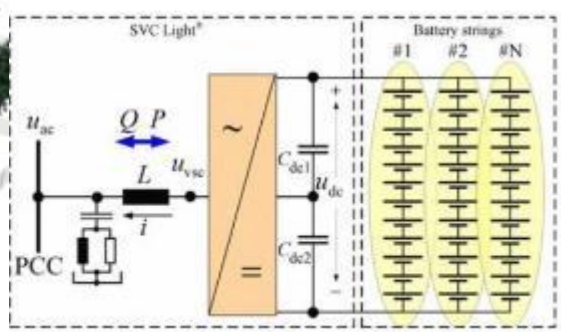
Power – short discharges (sec to min):
flywheels, capacitors, SMES, some batteries

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



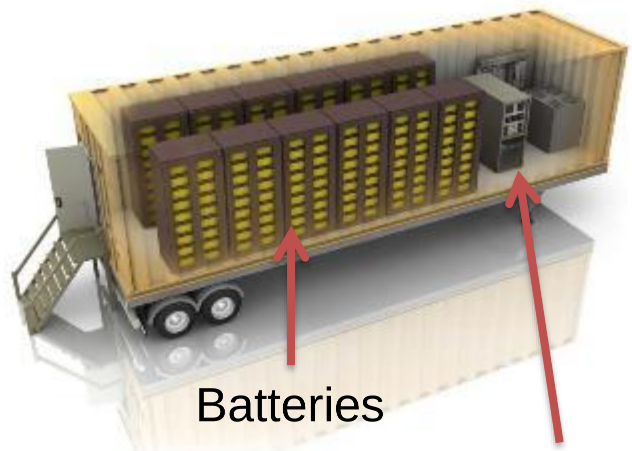
Examples of Large Energy Storage Demonstrations

- 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

Transportable Energy Storage Systems

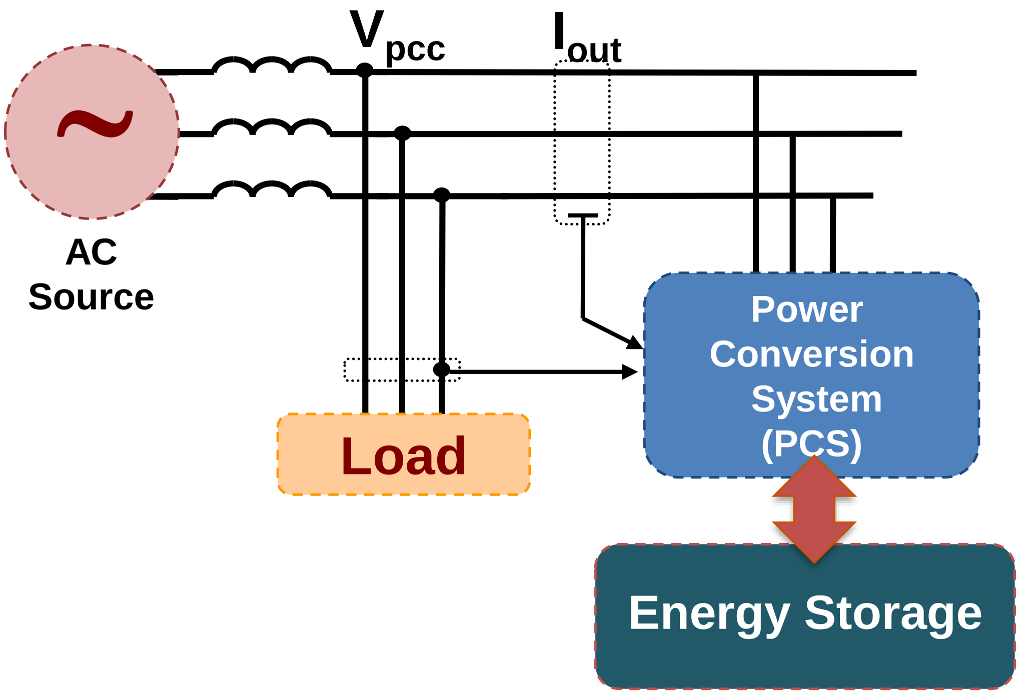


Benefits

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

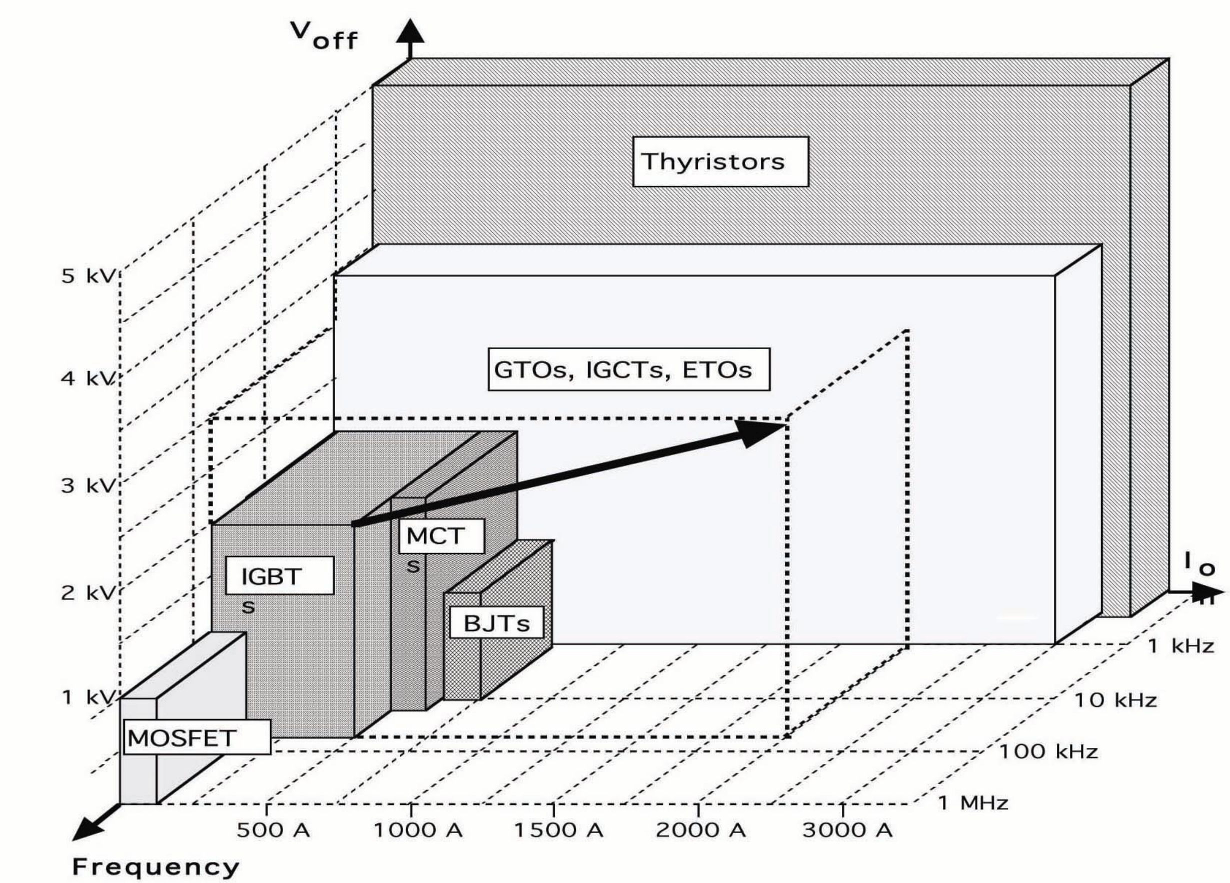
Why is DOE OE/Sandia interested in power electronics?

- 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.

Silicon Semiconductor Device Capabilities



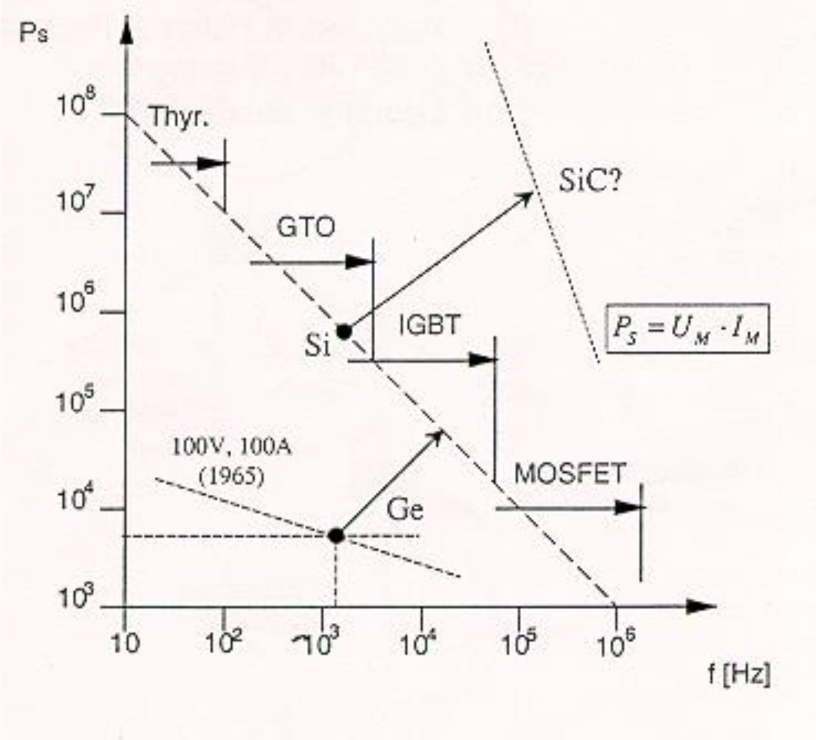
Trends:

- **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

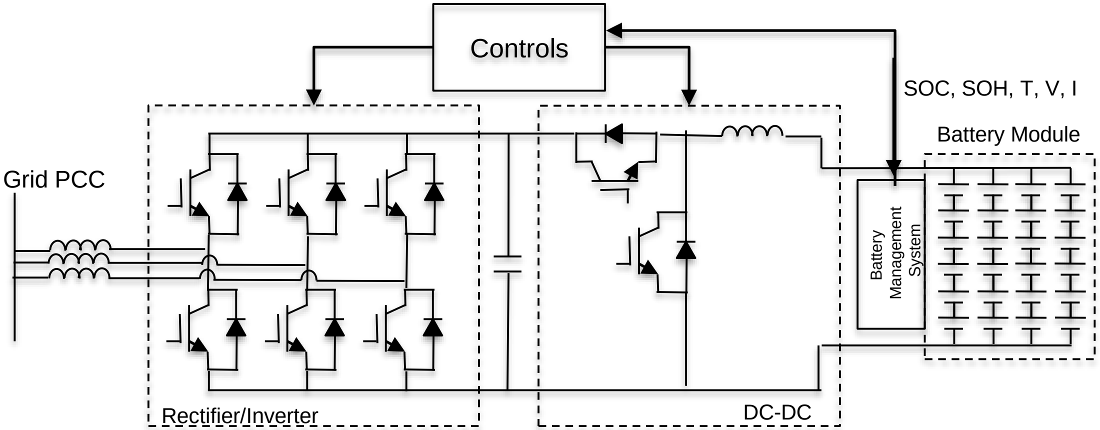


Source: Power Electronics Technology at the Dawn of the New Millenium – Status & Future

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

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

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

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

$\omega = angular\ velocity$

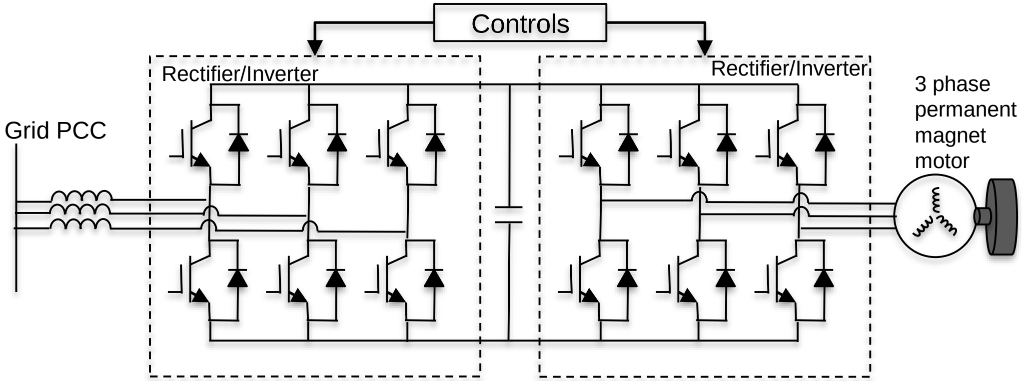
$I = moment\ of\ inertia$

$m = mass$

$r = radius$

- 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



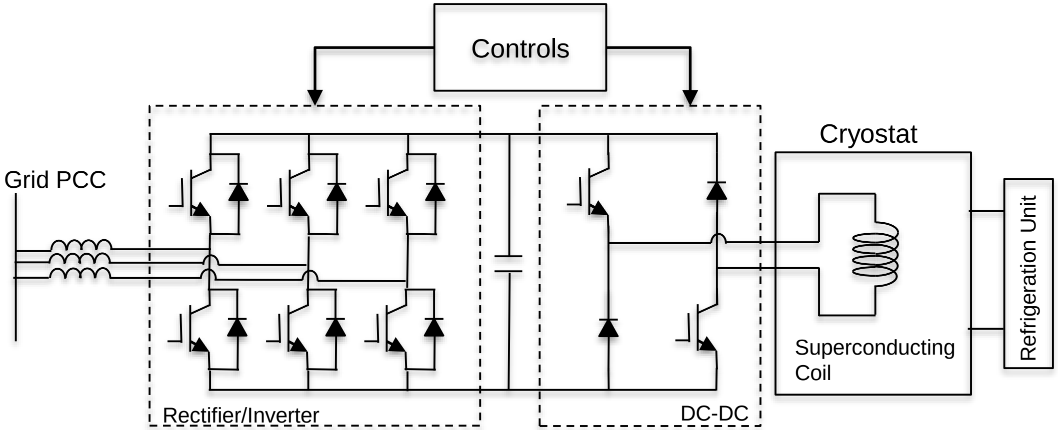
Typical Electrical Configuration of a FWES

Superconducting Magnetic Energy Storage System

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

- 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

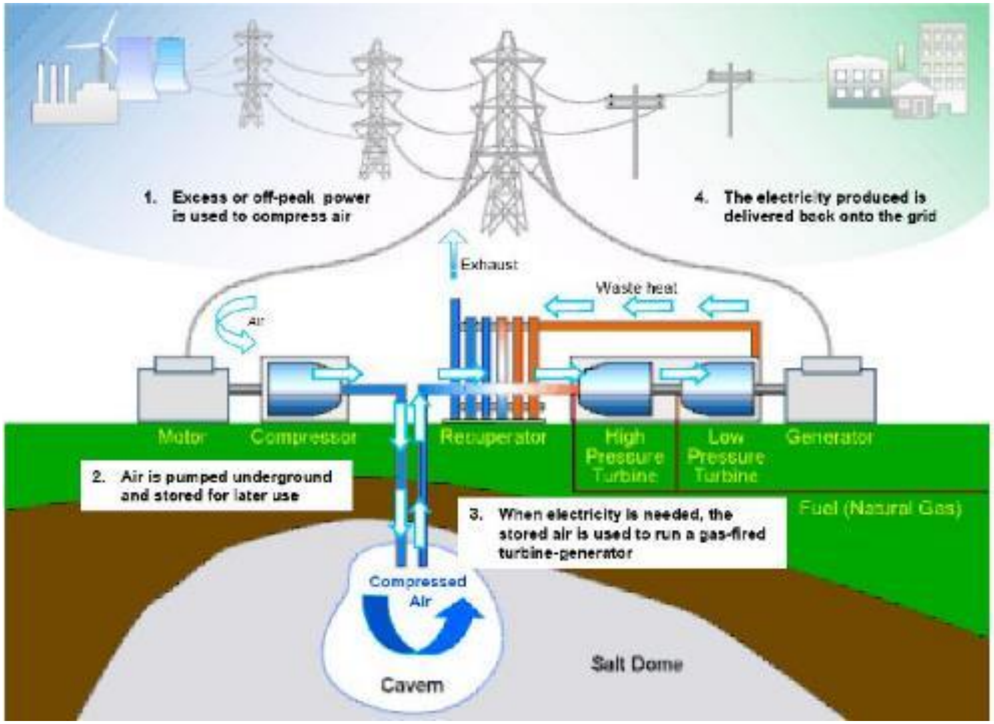
Source: T. Katagiri, H. Nakabayashi, T. Nijo, T. Tamada, T. Noda, N. Hirano, T. Nagata, S. Nagaya, M. Yamane, Y. Ishii, and T. Nitta, *Field Test Result of 10MVA/20MJ SMES for Load Fluctuation Compensation,* IEEE Transaction on applied Superconductivity, Vol. 19, No. 3, June 2009



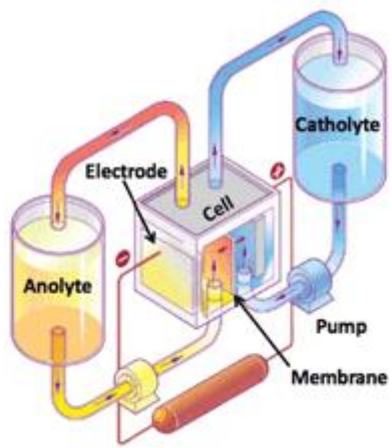
Typical Electrical Configuration of a SMES

Other Energy Storage Technologies

Electrochemical Capacitor Energy Storage

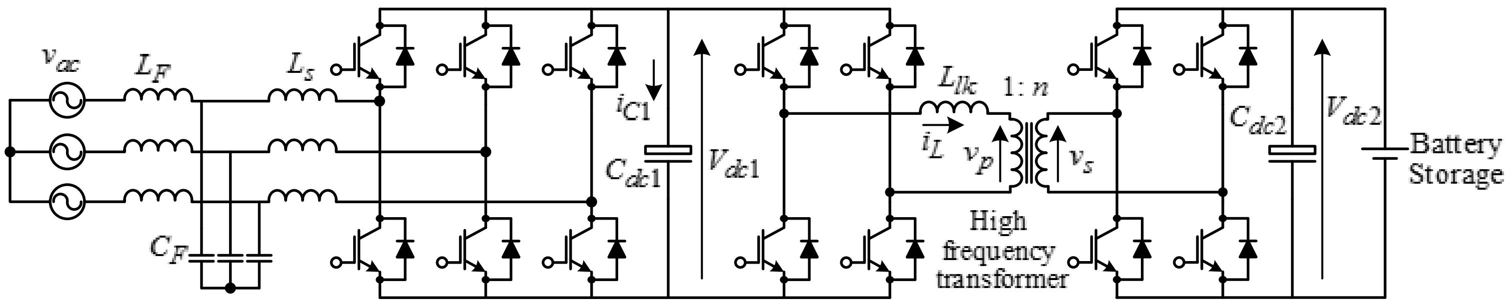


Compressed Air Energy Storage



Flow Battery Energy Storage

High Switching Frequency Benefits

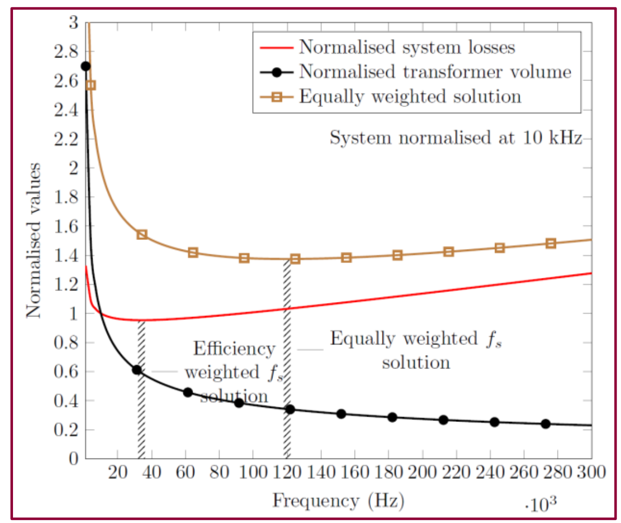


100 kHz Ferrite Transformer
8 kW – 328 grams (0.72 lbs)

60 Hz Si-Steel Transformer
7.5 kVA – 150 lbs

Source: Wolfspeed

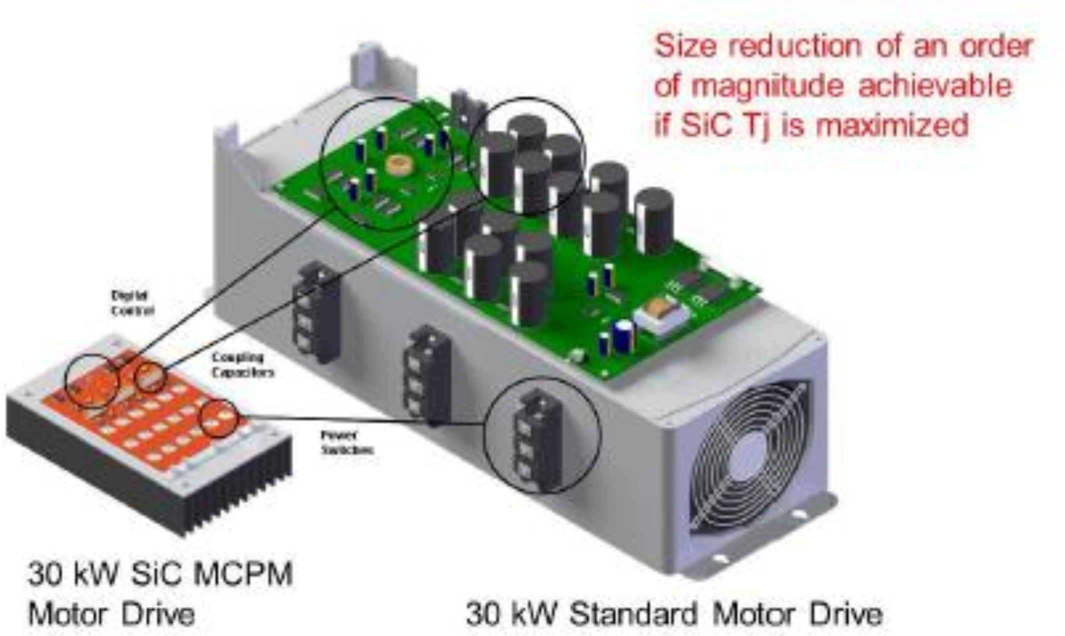
High frequency γ'-Fe_4N core can meet all requirements of high frequency power electronics



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

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



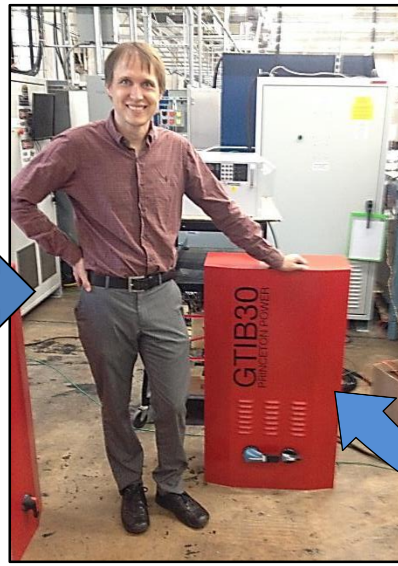
Source: Wolfspeed

Example: 30kW SiC Inverter

PRINCETON POWER SYSTEMS
Clean Power Made Simple™

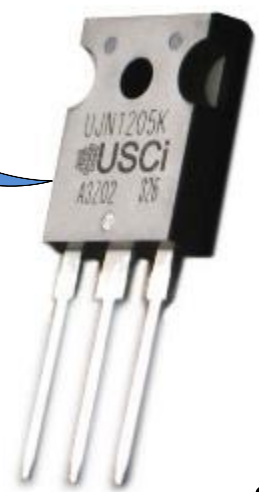
30kW Bidirectional Inverters

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

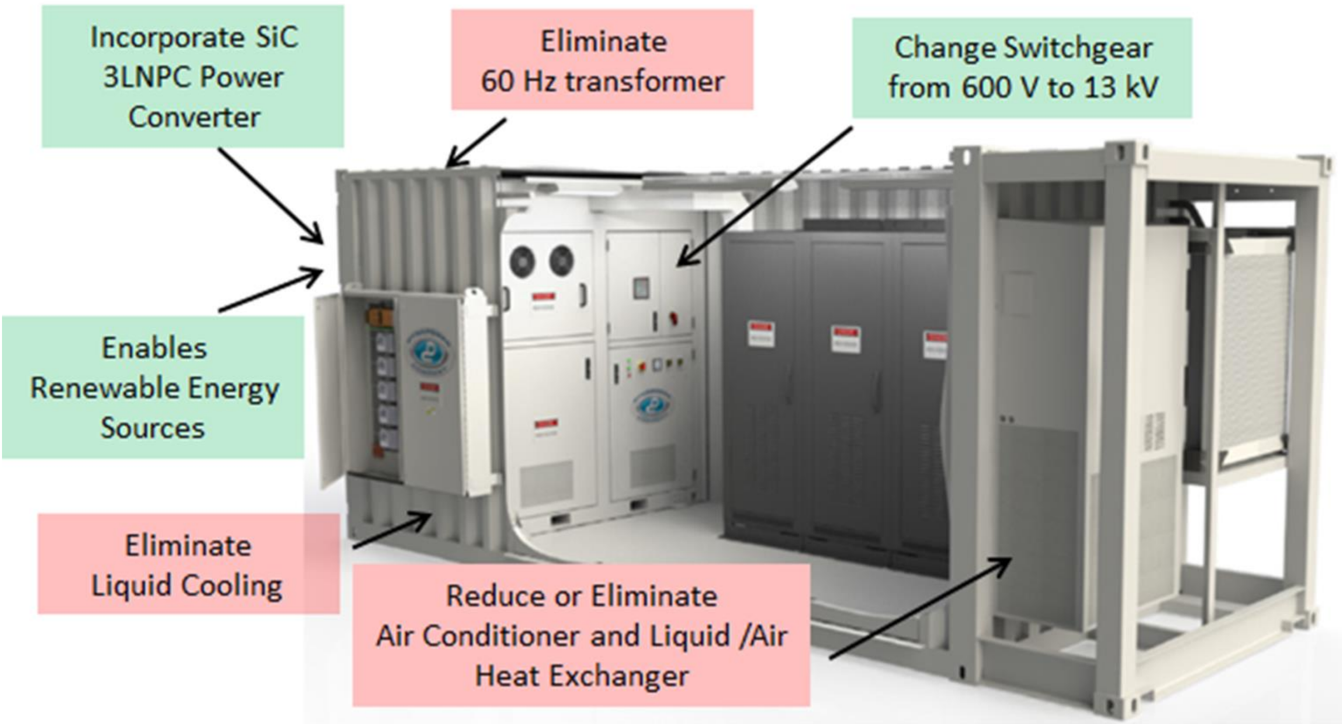
Parameter	Value	Unit
$R_{DS(on)}$	80	mΩ
V_{DS}	1200	V
T_{max}	175	°C

Source: USCi

Example: 500kW PCS using SiC

Existing 500 kVA Grid Tied Energy Storage Container (Dynapower)

Key: Eliminate Add

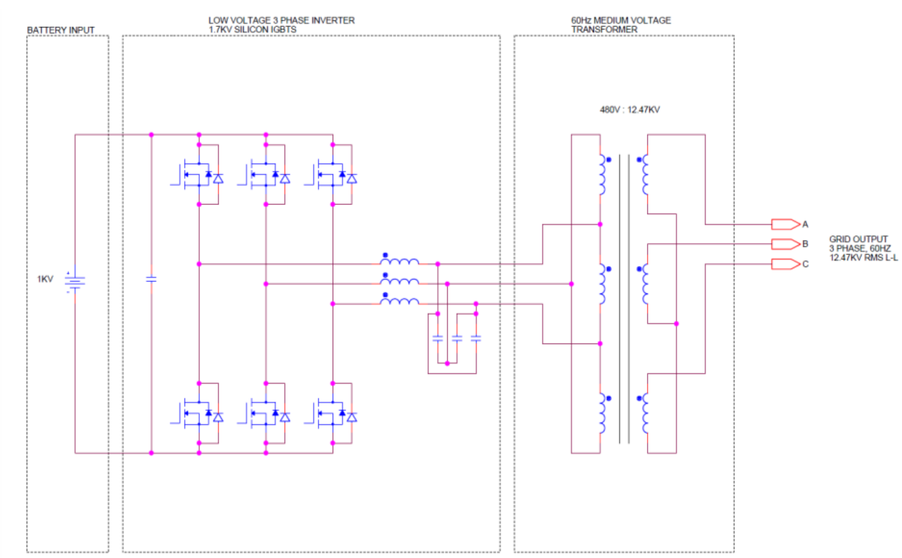


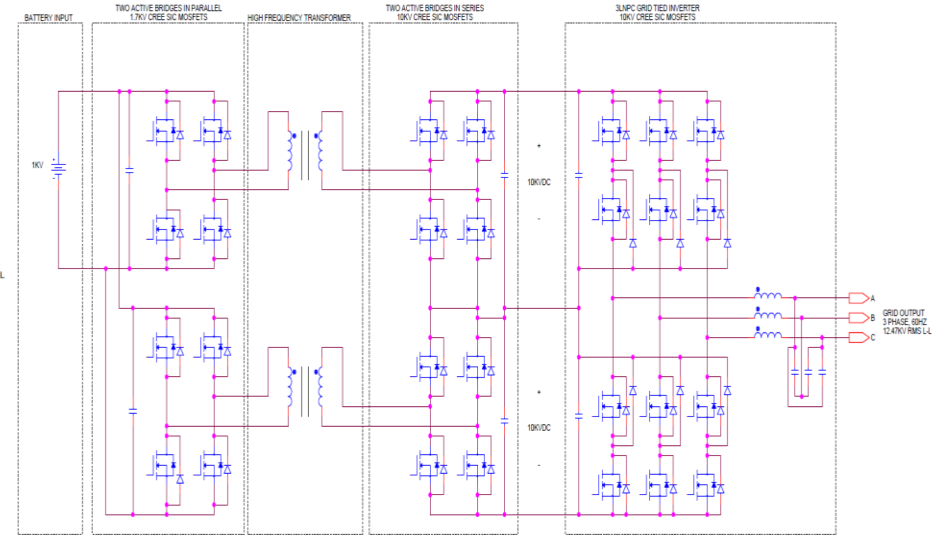
Nominal Existing Generation System

- 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>

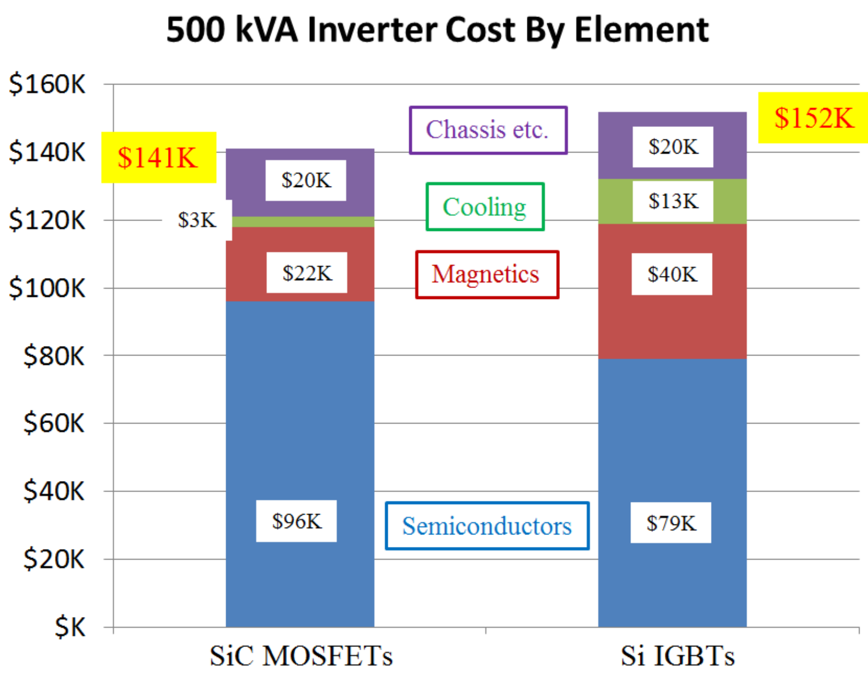
- Requires 480 : 12.47 kV transformer for grid connect.
- Silicon MOSFETs or IGBTs require liquid cooling (~ 50 °C).
- Filter is large and also requires liquid cooling.
- 60 Hz transformer emits acoustic noise.

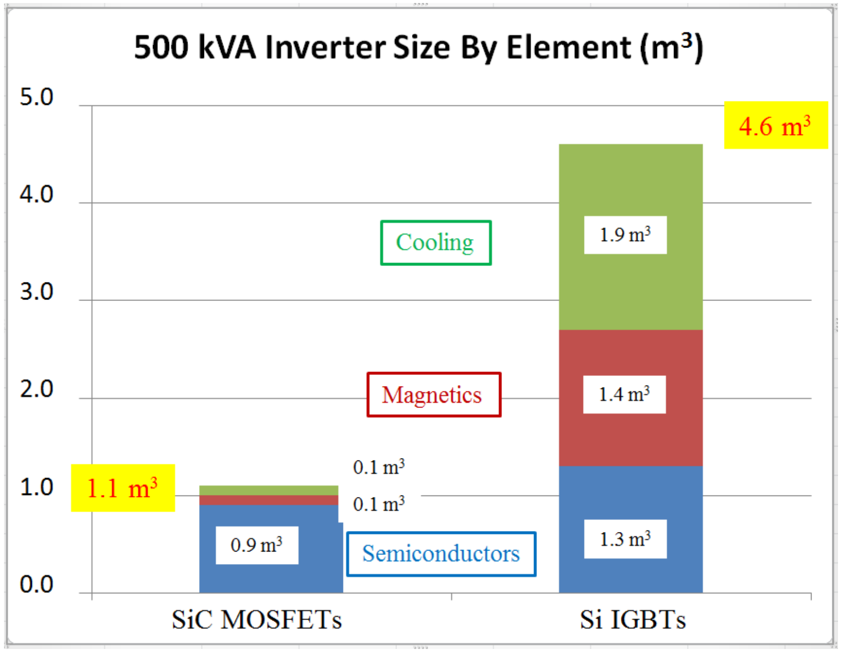
<u>Improvements:</u>

- 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



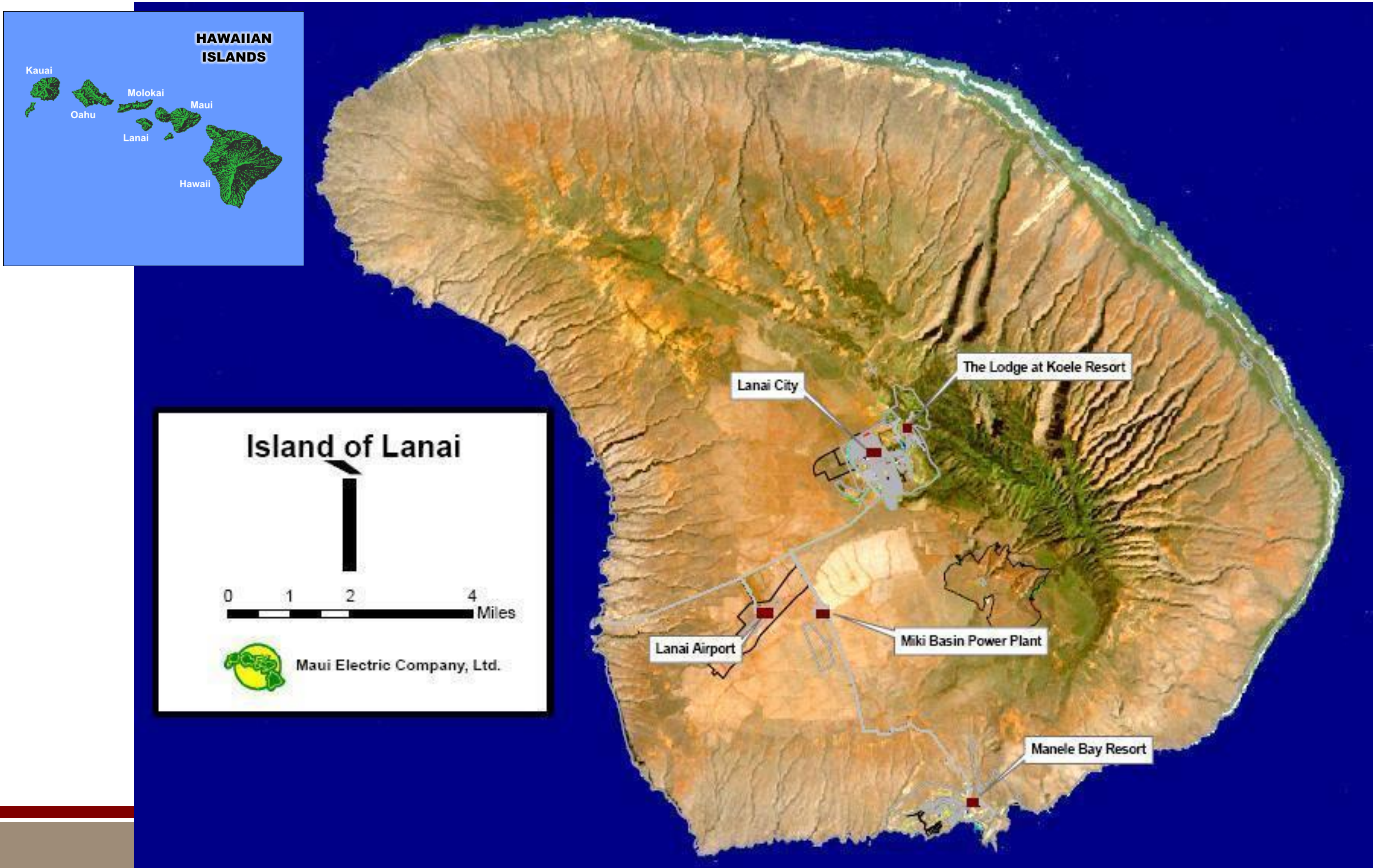


Per unit material costs are comparable ($141K vs. $152K). New design: SiC costs are higher, but magnetics and cooling costs are lower. **SiC costs are likely to reduce.**

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

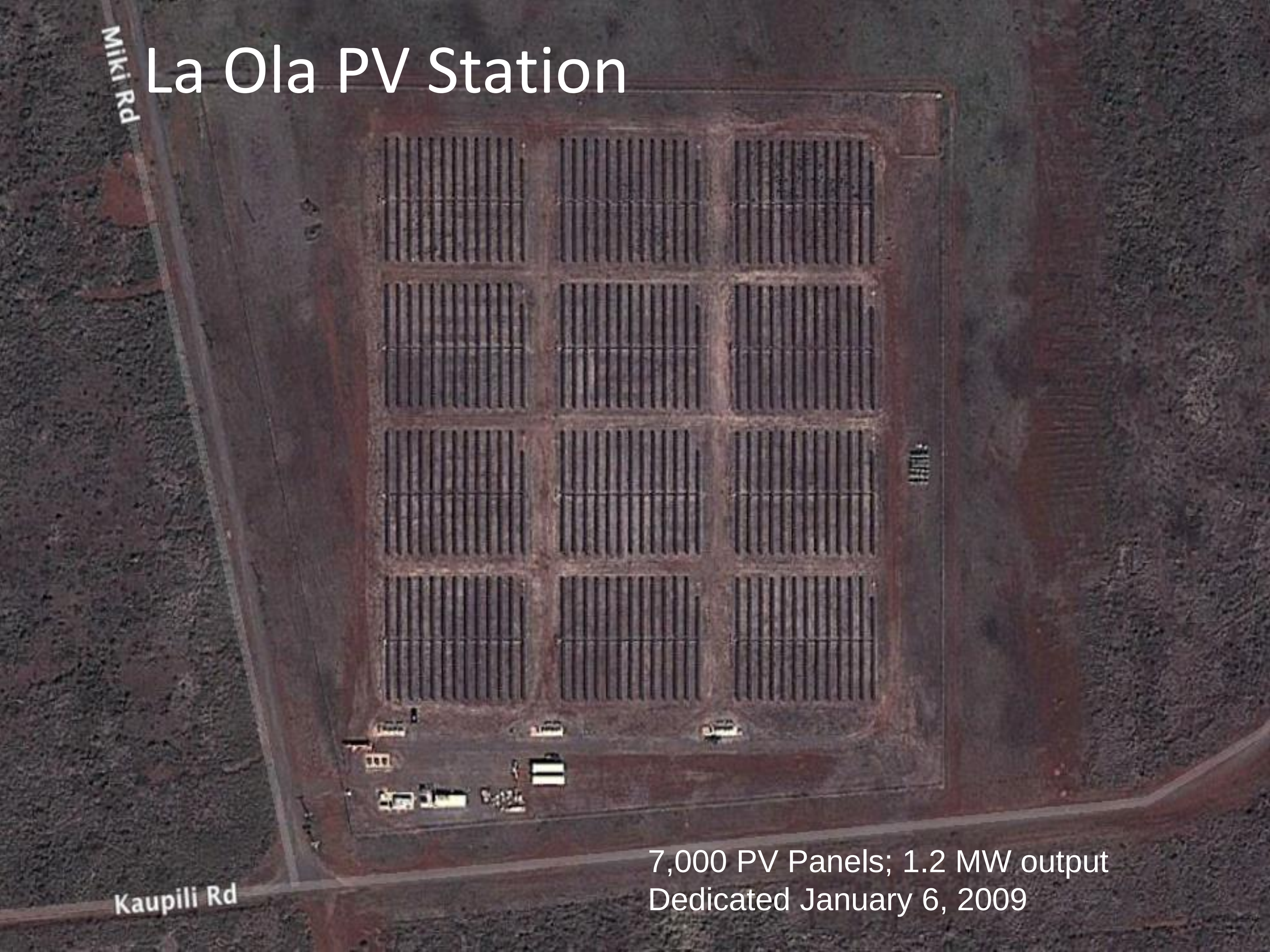
Courtesy: Creare, LLC

Lanai Battery Project



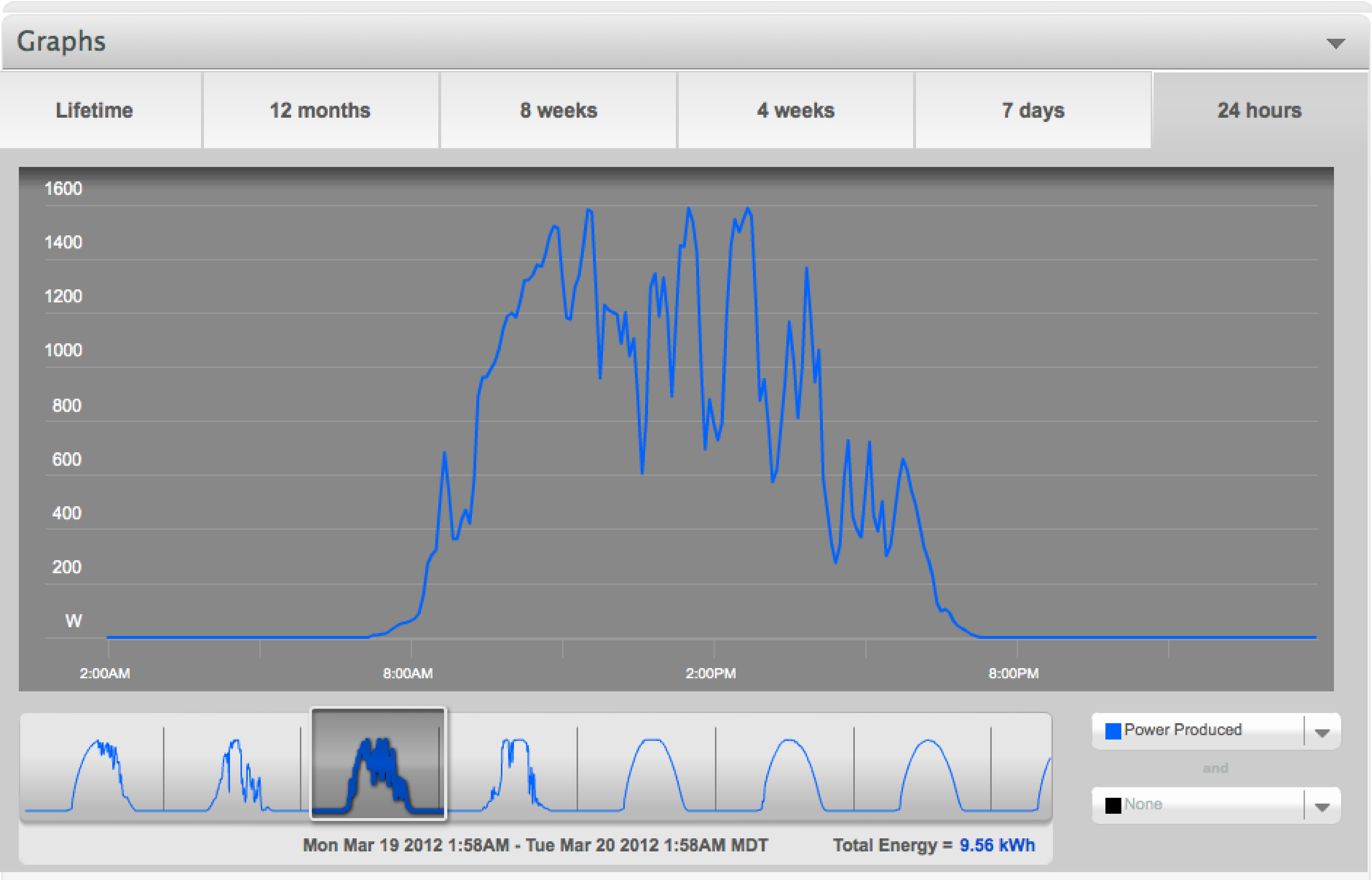
(6) 1.0 MW EMD Diesel Generators
(2) 2.2 MW Caterpillar Diesel

La Ola PV Station

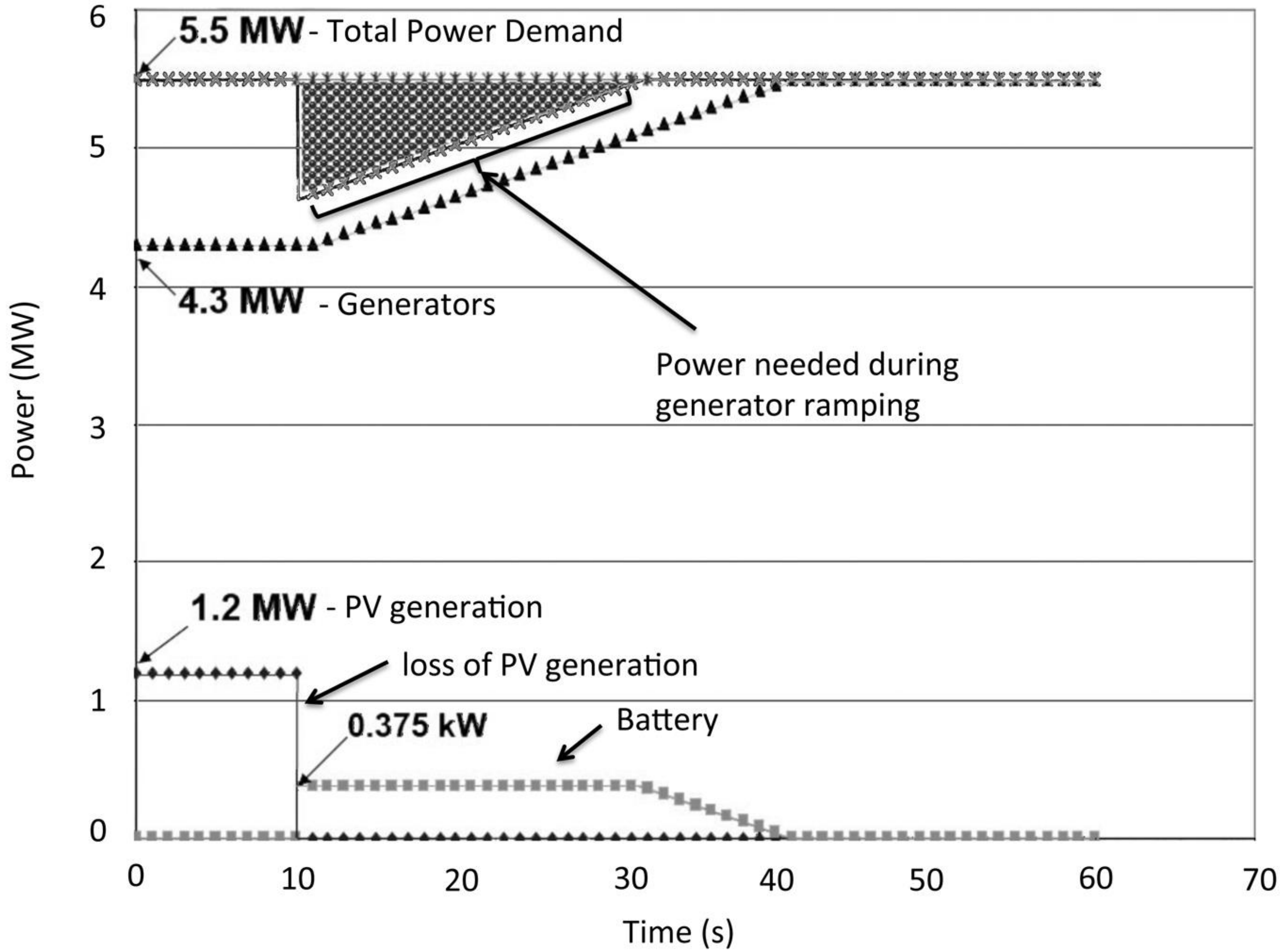


7,000 PV Panels; 1.2 MW output
Dedicated January 6, 2009

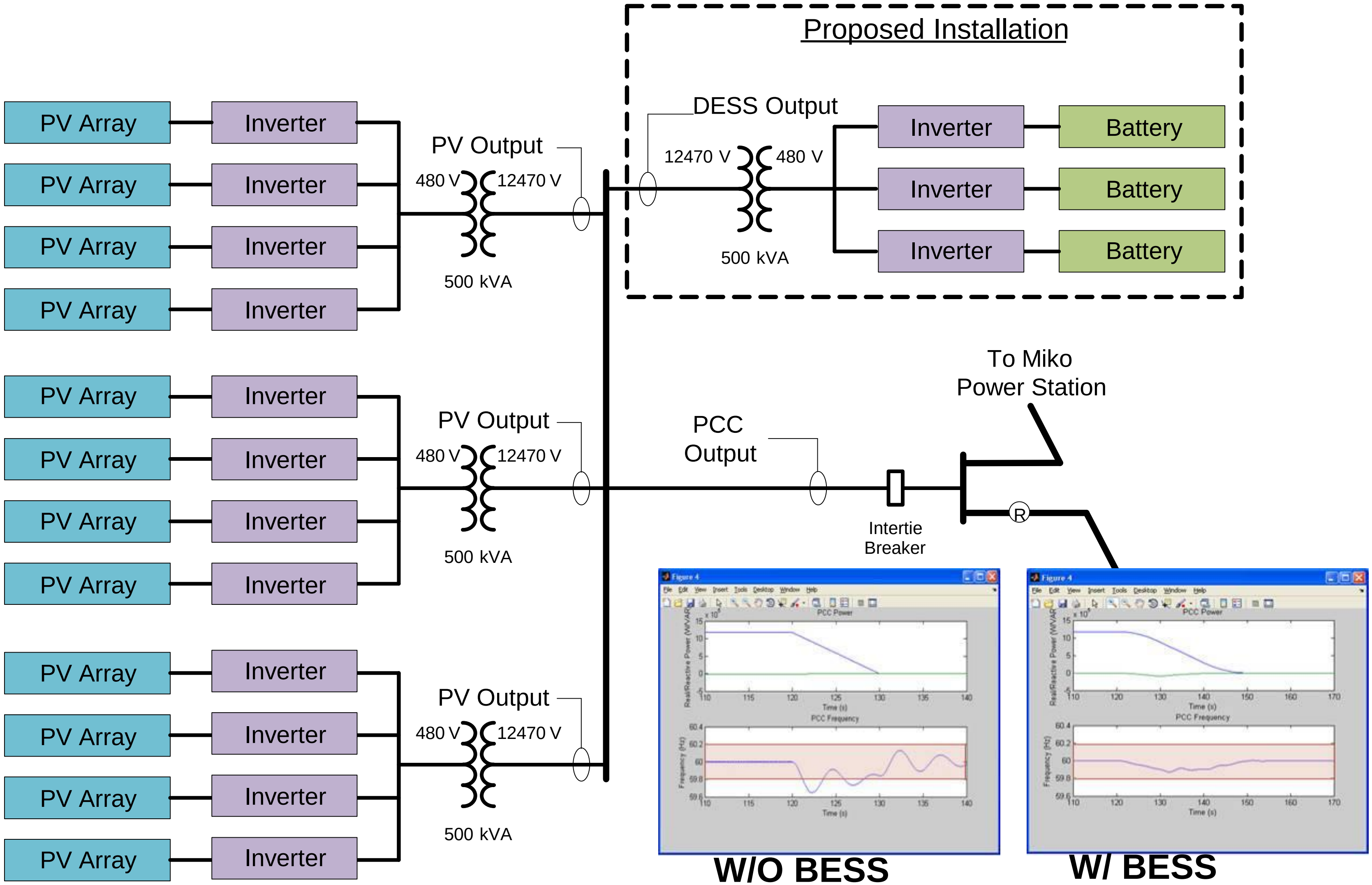
Variability of PV Output



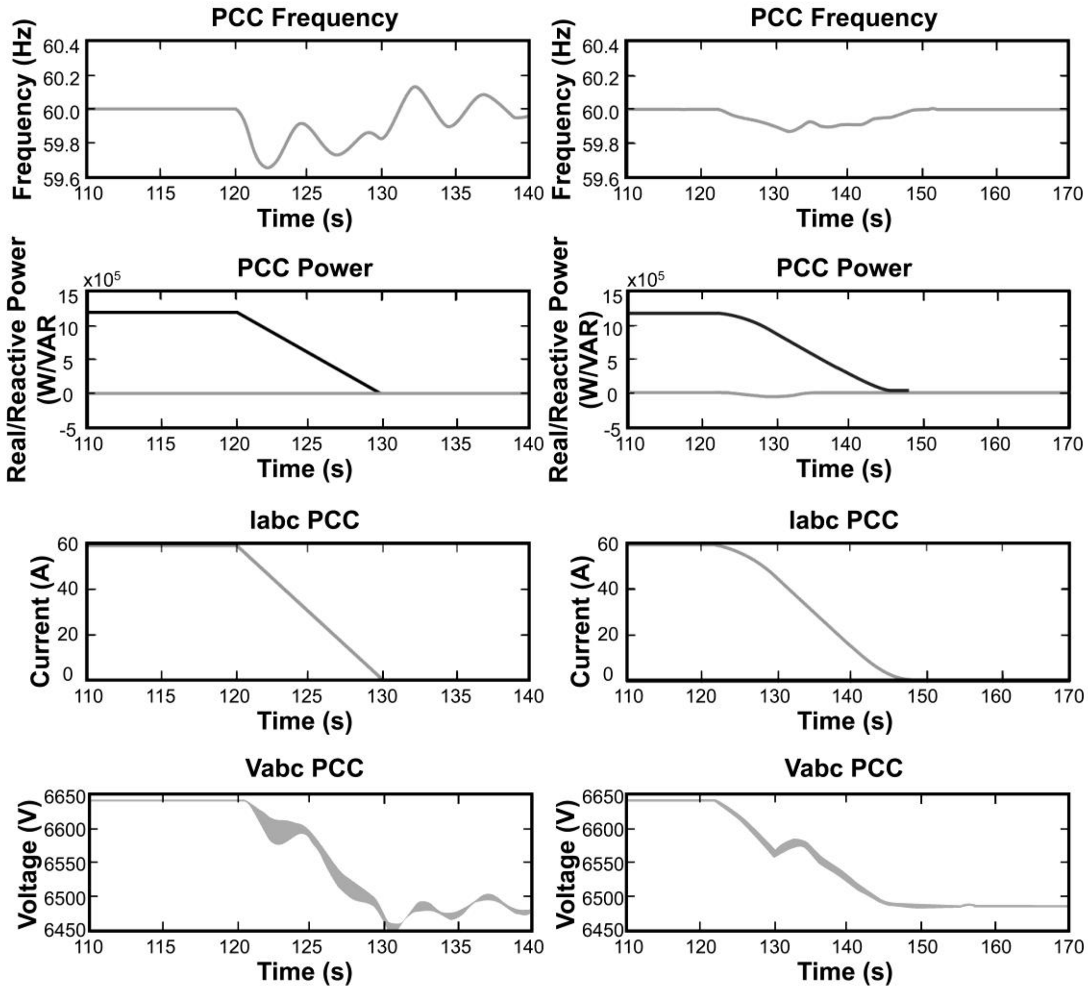
How Energy Storage Smooths PV



Lanai Grid Energy Storage Control Project



Frequency Response to ramp-rate control



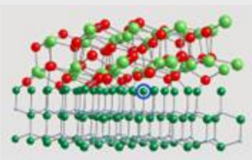
Source: Power Eectronics for Renewable and Distributed Energy Systems, Sprigner Verlag, 2013

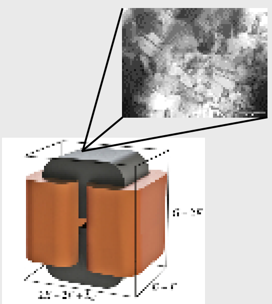
Lanai Battery

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

Energy Storage Power Electronics Program

Materials R&D



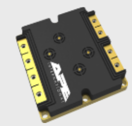


- Gate Oxide R&D
- Advanced Magnetics

Devices

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

Power Modules

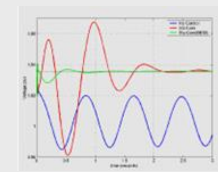


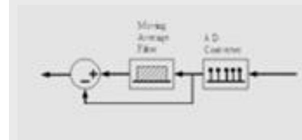
- SiC High Temp/density Power Module
- HV SiC JFET Module
- HV, HT Reworkable SiC half-bridge modules

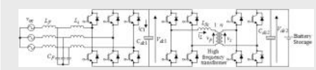
Power Conversion System

- 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

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