SAND2022-1589C

Grid-tied Energy Storage and Power Conversion Systems

Stan Atcitty, Ph. D.

Valerio De Angelis, Ph. D.

Sandia National Laboratories

Presented at APEC 2022

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Bios

Stan Atcitty, Ph.D. Electrical Engineer
Distinguished Member of the Technical Staff

Dr. Atcitty received his BS and MS degree in electrical engineering from the New Mexico State University in 1993 and 1995 respectively. He received his PhD from Virginia Tech University in 2006.

He is presently a Distinguished Member of Technical Staff at Sandia National Laboratories in the Energy Storage Technology & Systems department. He has worked at Sandia for over 25 years. His interest in research is power electronics necessary for integrating energy storage and distributed generation with the electric utility grid. He leads the power electronics subprogram as part of the DOE Office of Electricity Energy Storage Program.

Valerio De Angelis, Ph.D. Chemical Engineering
Distinguished Member of the Technical Staff

Dr. De Angelis joined Sandia in 2020 to work on battery modeling, system integration, advanced manufacturing, and long-term energy storage. He is co-founder of batteryarchive.org, the first public repository for easy visualization and comparison of lithium-ion battery degradation data across institutions.

Before joining Sandia National Laboratories, Dr. De Angelis was the Executive Director of the City University of New York (CUNY) Energy Institute and a co-founder of Urban Electric Power. which is commercializing rechargeable Zn-Mn batteries.

Previously, De Angelis was the CEO and CTO of Mindflash Technologies, a leading provider of online training platforms that he founded when he was a Ph.D. student at UC Santa Barbara and brought to profitability and acquisition.

Energy storage and power electronics program at Sandia

BATTERY MATERIALS
Large portfolio of R&D projects related to advanced materials, new battery chemistries, electrolyte materials, and membranes.

CELL & MODULE LEVEL SAFETY
Evaluate safety and performance of electrical energy storage systems down to the module and cell level.

POWER CONVERSION SYSTEMS
Research and development regarding reliability and performance of power electronics and power conversion systems.

SYSTEMS ANALYSIS
Test laboratories evaluate and optimize performance of megawatt-hour class energy storage systems in grid-tied applications.

DEMONSTRATION PROJECTS
Work with industry to develop, install, commission, and operate electrical energy storage systems.

STRATEGIC OUTREACH
Maintain the ESS website and DOE Global Energy Storage Database, organize the annual Peer Review meeting, and host webinars and conferences.

GRID ANALYTICS
Analytical tools model electric grids and microgrids, perform system optimization, plan efficient utilization and optimization of DER on the grid, and understand ROI of energy storage.

Wide ranging R&D covering energy storage technologies with applications in the grid, transportation, and stationary storage

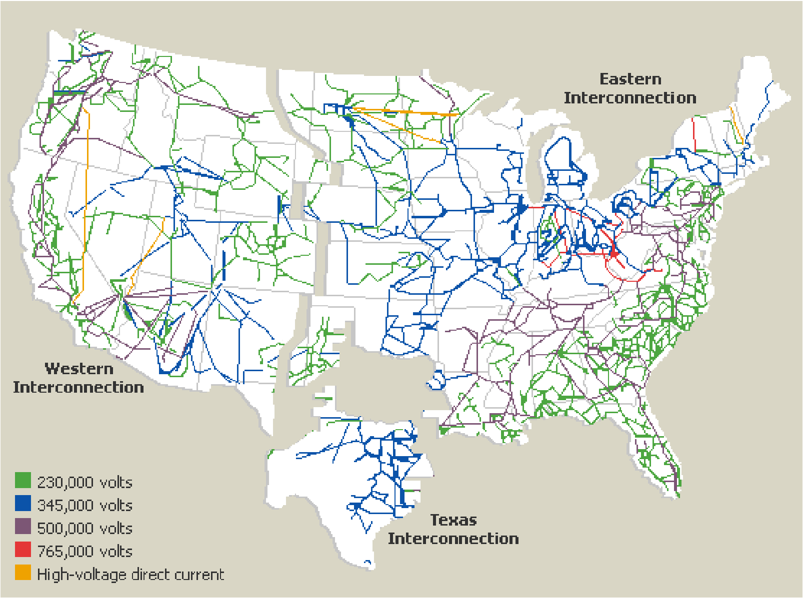
Why This Topic Matters

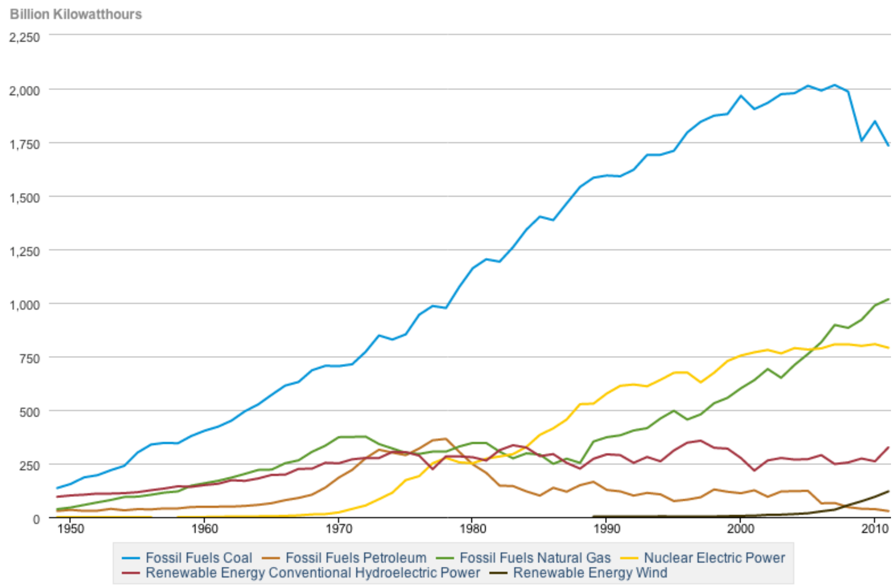
- Renewable generation is increasing
- Traditional generation is decreasing
- There is a need for Energy Storage at different scales
  - < 6 hours: Li-ion
  - 12-24 hours: Flow batteries
  - > 1 day: chemical, thermal, and gravity-based systems
- New Power Electronics topologies are needed to integrate different energy storage technology.
- The industry needs modular and reusable power electronics, control software, and data acquisition systems.

Current Status: Status of the US electric grid

Made up of:

- 7,300 power plants
- Over 150 thousand miles of transmission lines (AC & DC)
- Millions of transformers, relays, and controls
- Millions of miles of low-voltage power lines connecting over 145 million customers
- 100s of billions of dollars in total investments in transmission and distribution
- Coal generation is decreasing and natural gas generation is increasing. Renewable generation is still only 10%.

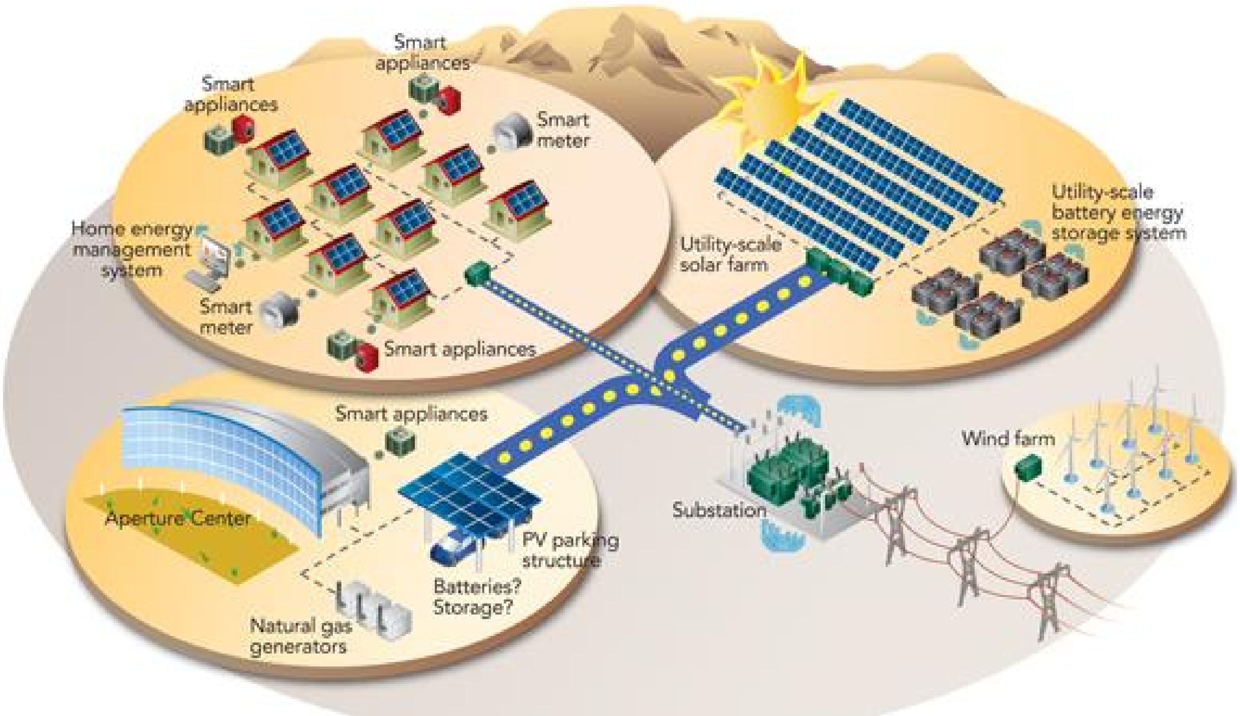


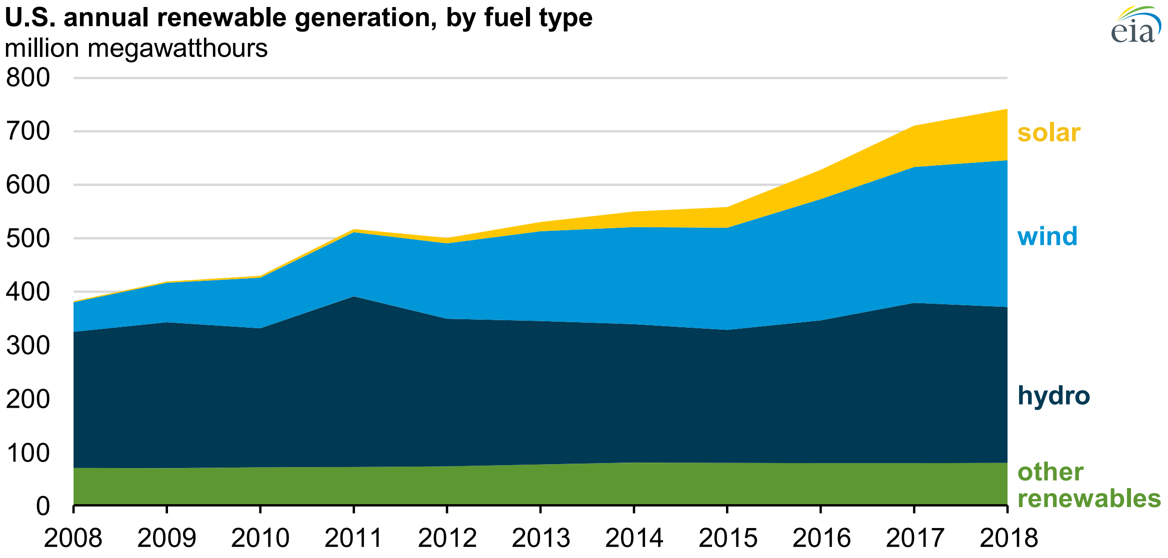


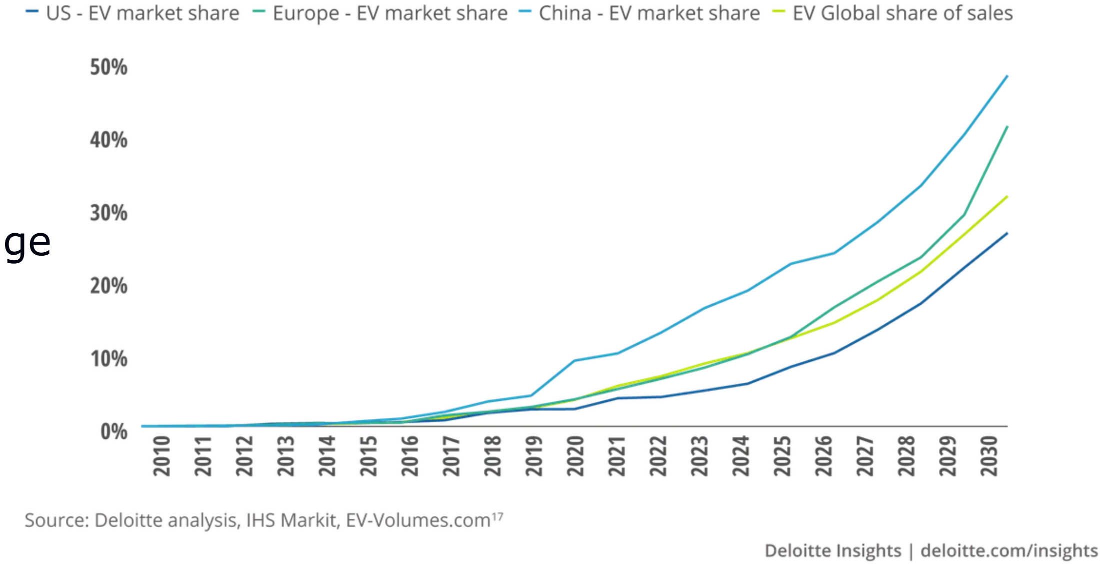
Trends challenging the grid:

- Changing generation mix
- Aging infrastructure
- Increased variable generation and load mix
- Increased cyber and physical attacks
- Changing demands

Current Status: The importance of renewable generation and energy storage



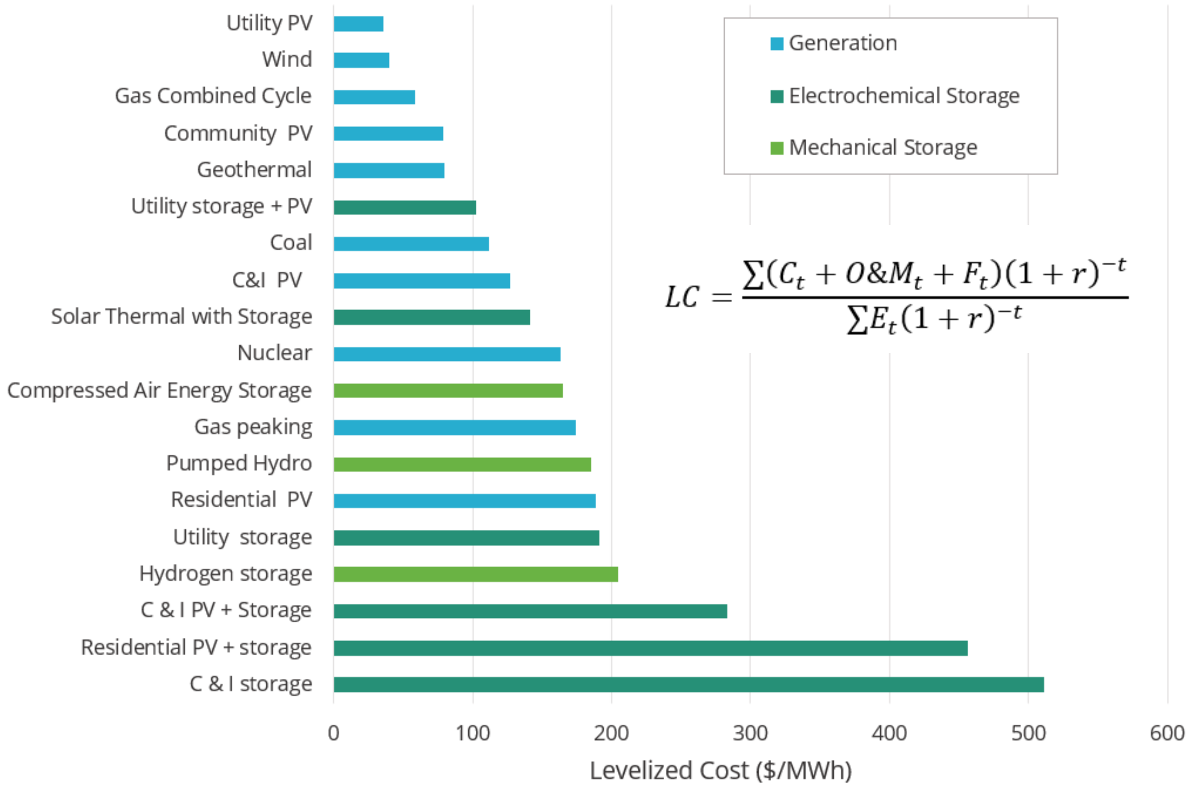




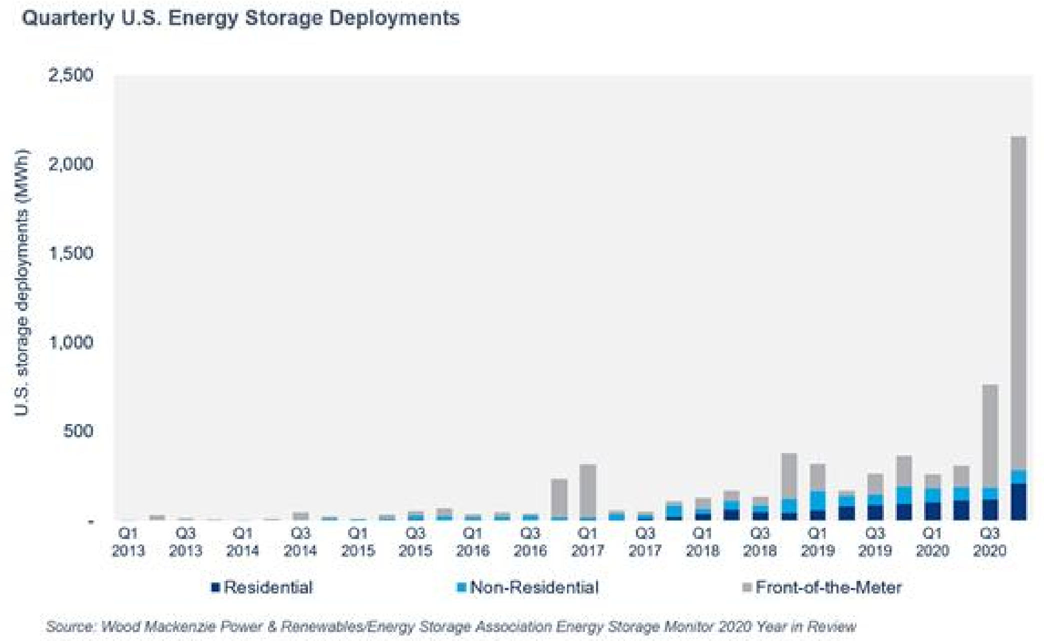
Renewable generation and the growth of electric vehicles are accelerating grid modernization and the need for energy storage at various points on the grid.

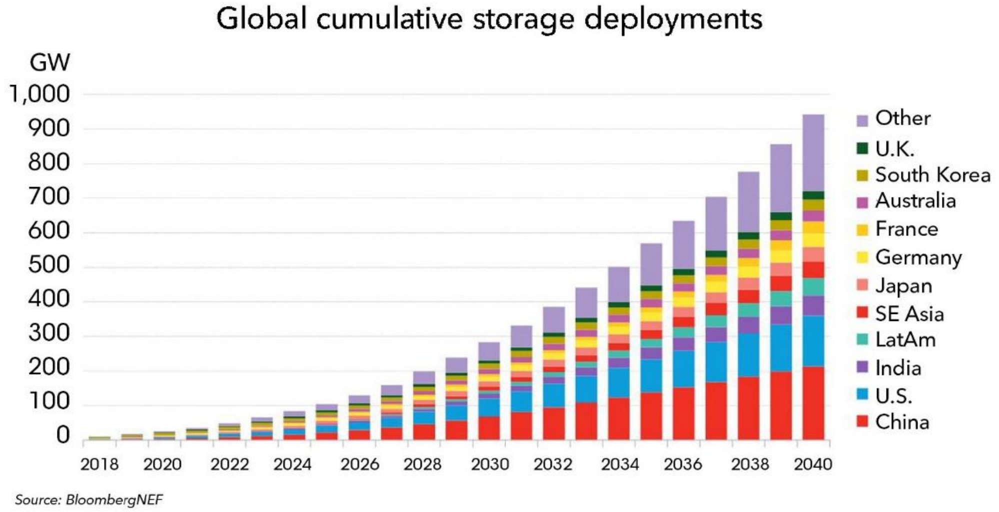
Energy storage is needed to shift renewable generation, add inertia to the grid, and compensate, locally, for the additional peak demand brought by EV charging stations.

Current Status: Energy storage costs are decreasing and deployment increasing



$$LC = \frac{\sum(C_t + O\&M_t + F_t)(1+r)^{-t}}{\sum E_t(1+r)^{-t}}$$





Utility storage + PV with 2-4 hours of energy storage is competitive with Coal and Nuclear.

Grid-scale storage installations are growing and are expected to continue to grow worldwide.

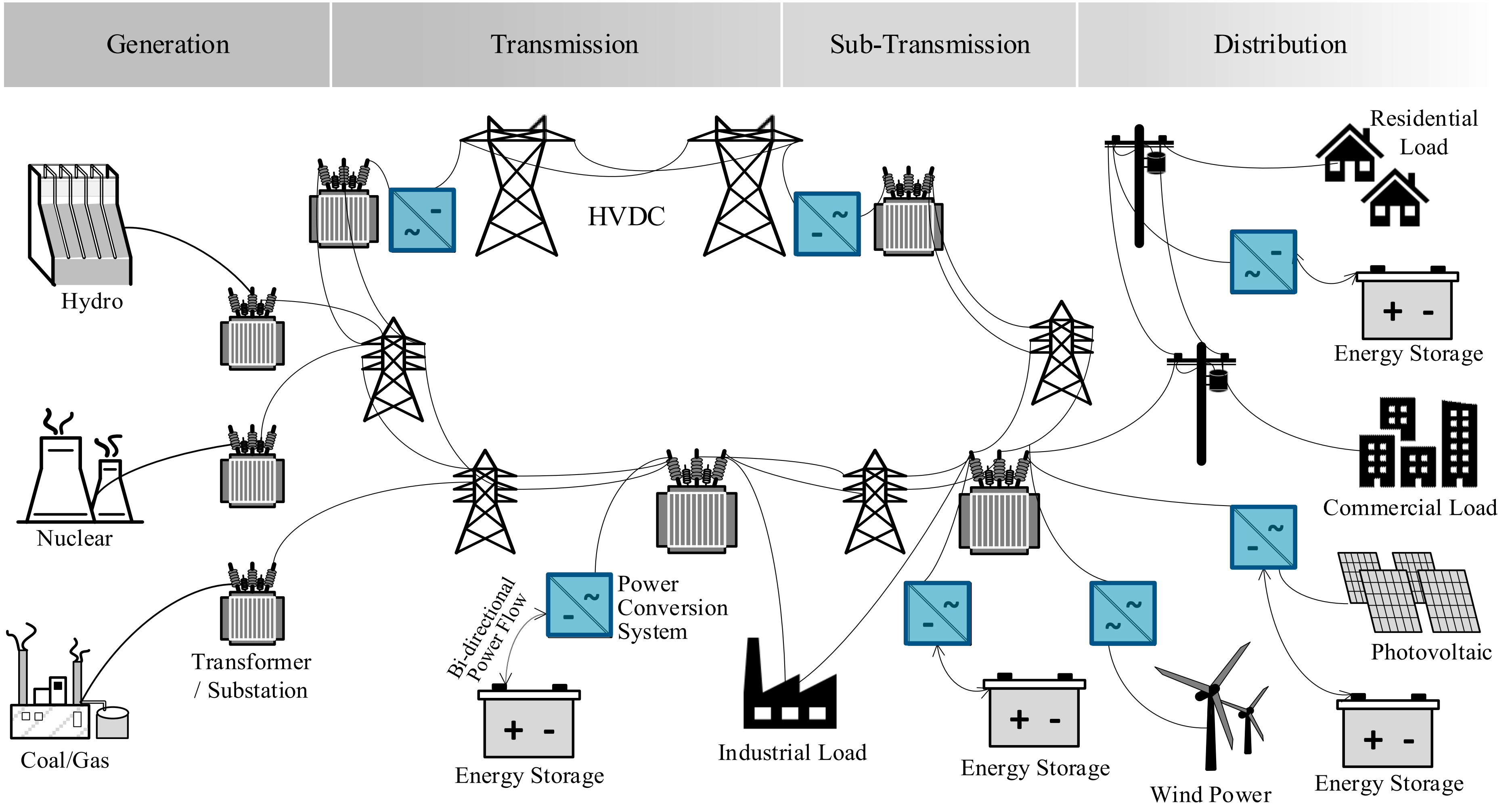
Over time, the growth of the market will be limited by the competition from Li-ion cells from the EV markets.

The expanding role of power electronics

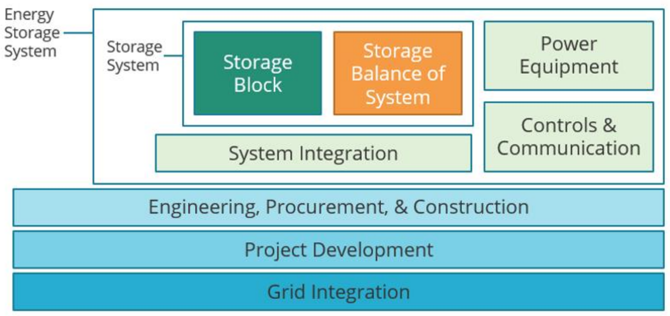
Power electronics provides two critical services

- Efficient conversion between disparate forms of electricity
- Unprecedented control over the flow of energy

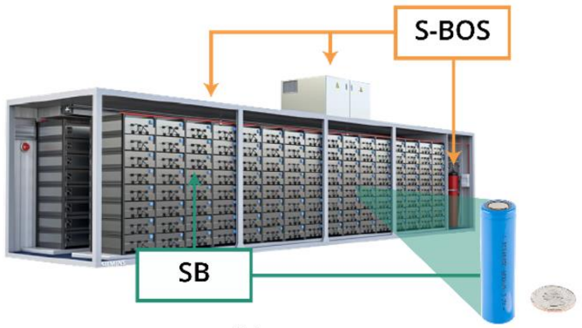
Power electronics are the most potent tools at our disposal for modernizing transmission, distribution, and utilization.



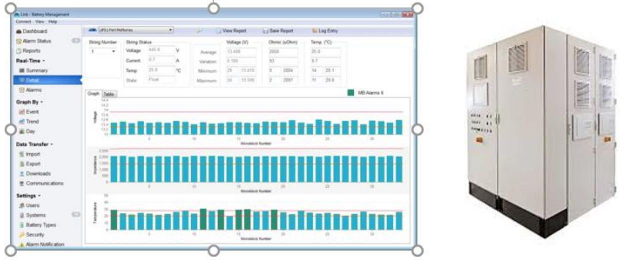
Energy storage system components



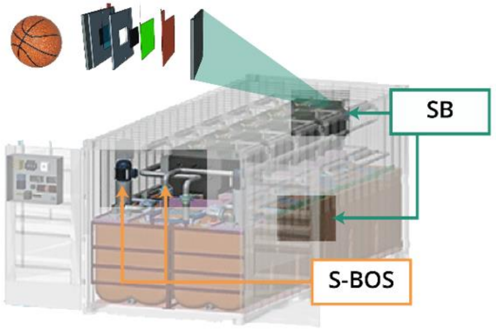
(a) ESS components



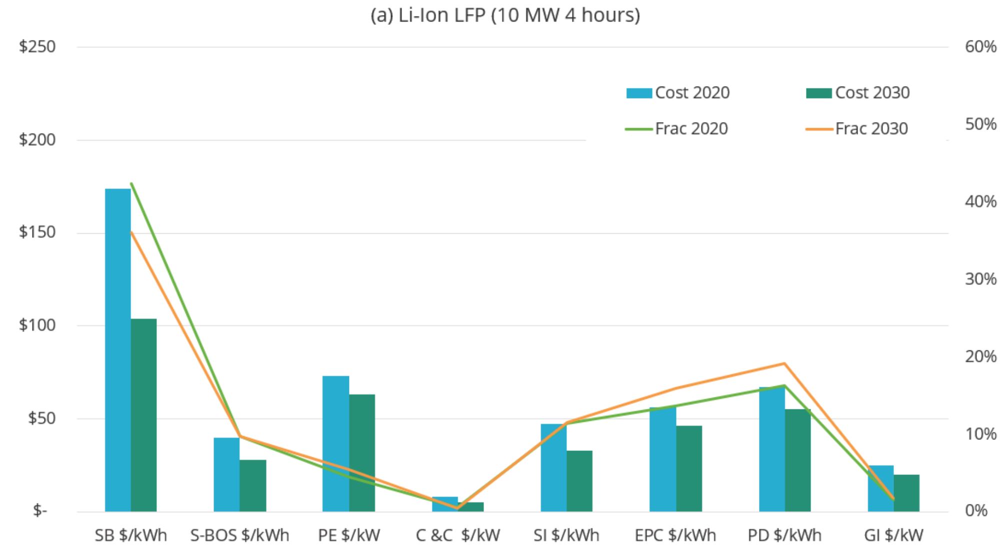
(b) 18650 Li-ion ESS

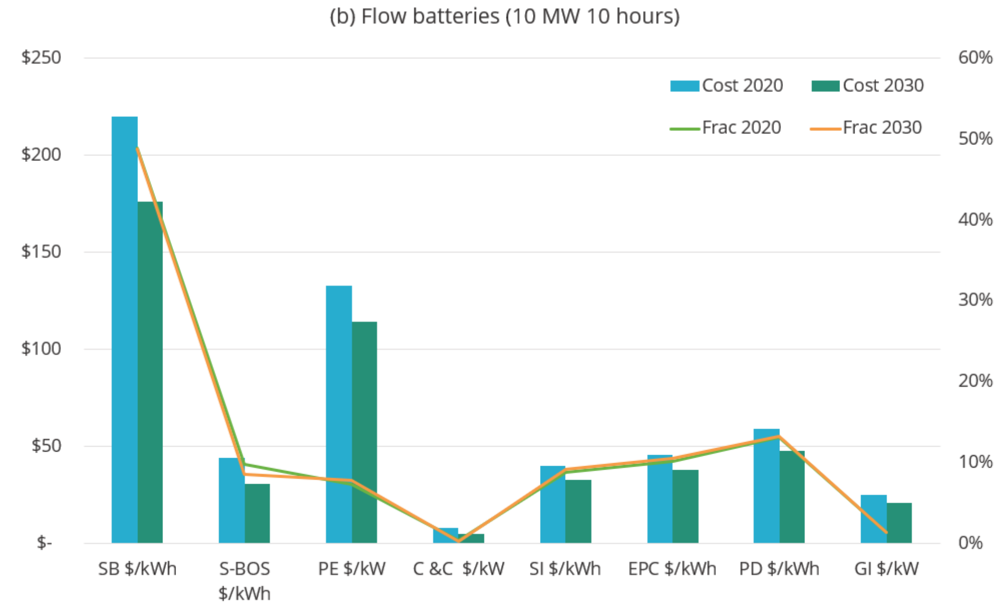


(d) Software and Power Converters



(c) Flow battery



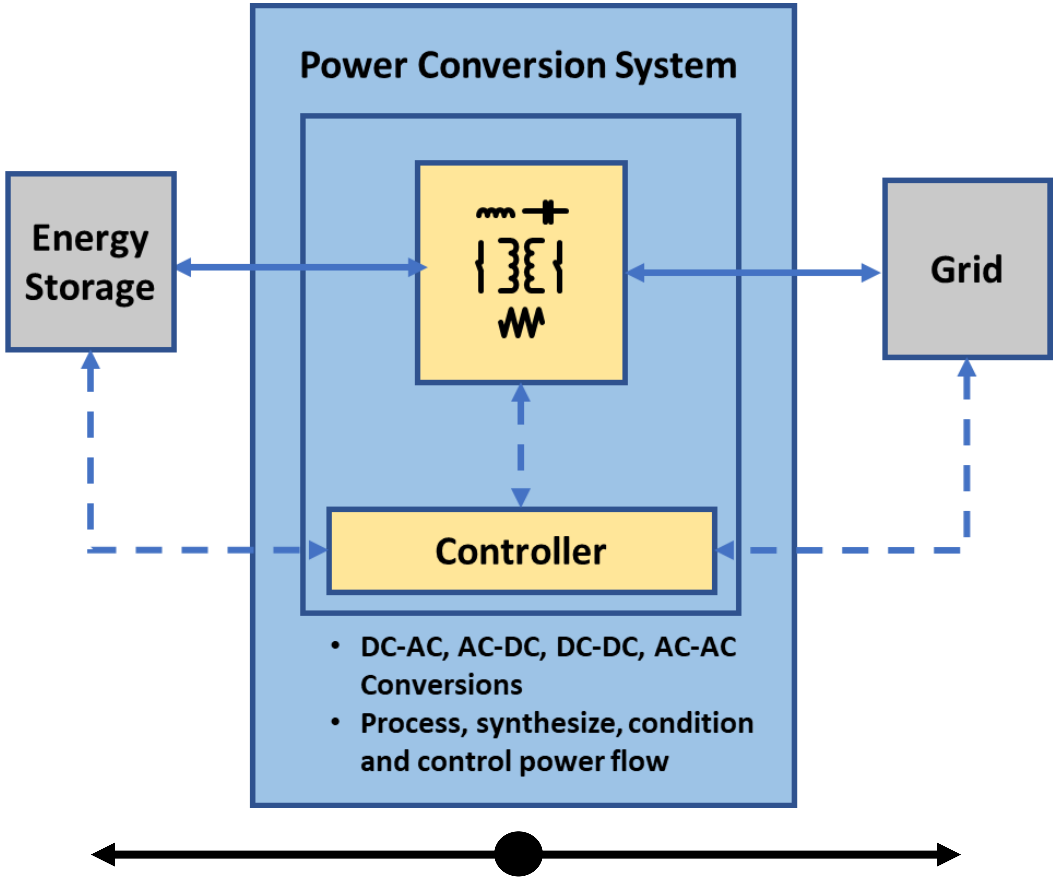


Energy storage systems include multiple components. The Storage Block accounts for < 50% of the total cost.

It is important to work on system standardization (power electronics, data communication, and software controls) to accelerate cost reduction and facilitate adoption.

Energy storage system components

- Power conversion systems (PCS), sometimes referred to and used interchangeably as power electronics, are a key enabling technology for energy storage.
- In a grid-tied energy storage system, the PCS controls the power supplied to and absorbed from the grid, simultaneously optimizing energy storage device performance and maintaining grid stability.
- There are multiple types of energy storage technologies, and each has their own characteristics and control parameters that must be managed by the PCS.
- An energy storage installation may be tasked with a variety of different grid support services; the PCS is responsible for controlling the flow of energy to meet the requirements of the intended grid support application.
- The major electrical components of a PCS are semiconductor switches, magnetic devices such as inductors and transformers, capacitors, and a controller.



Storage Interface

- Charge/Discharge Procedures
- DC Bus Regulation
- Balancing and Protection

Grid Interface

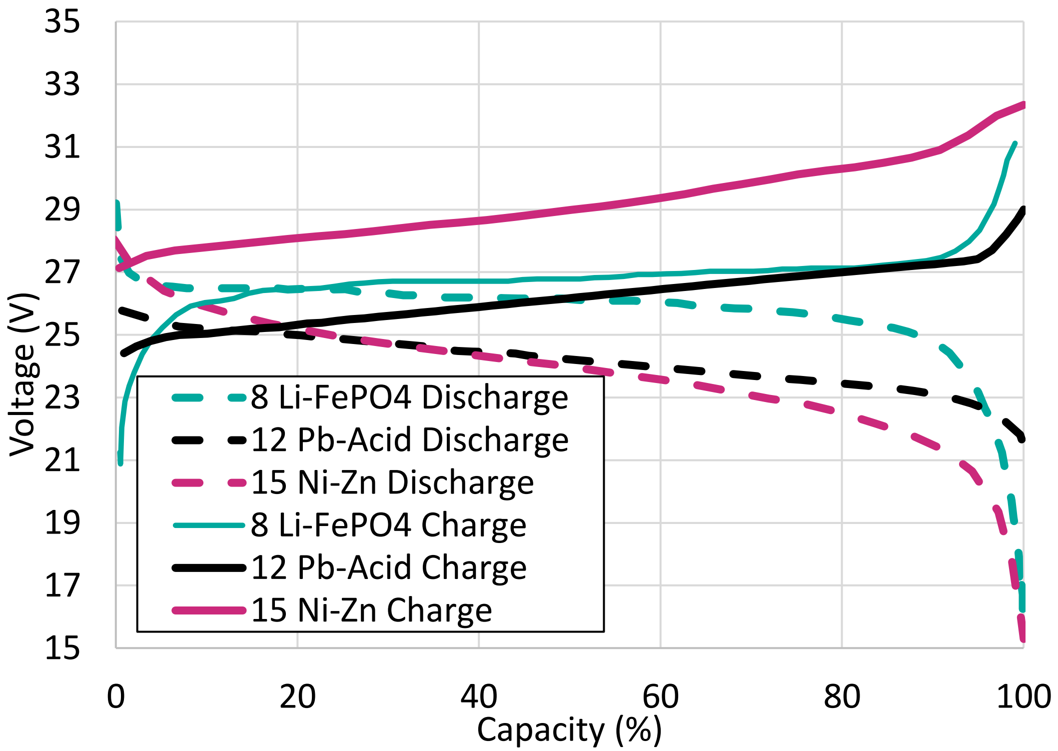
- Current and Voltage Regulation
- Grid Synchronization
- Application Specific Power Flow Control

Battery energy storage systems

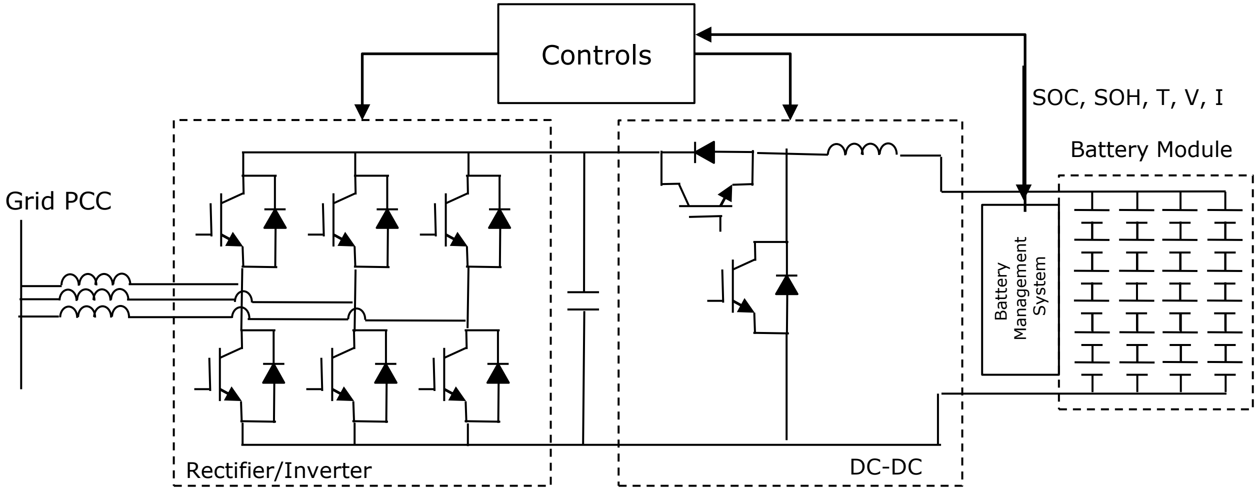
- Electrochemical energy storage devices are not ideal voltage sources and need to be managed
- Consist of one or more cells, main components include cathode (+)/anode (-) terminals, electrolytes, and separator. Converts chemical energy to electrical energy.
- Pb-acid, Li-ion, NaS, Metal Air, Advanced Pb C, etc.
- Key design objectives – high cell voltage, high energy or power formats, safe systems, and high reliability

18650 Cell

Battery module



Voltage curves as a function of discharge and charge capacity



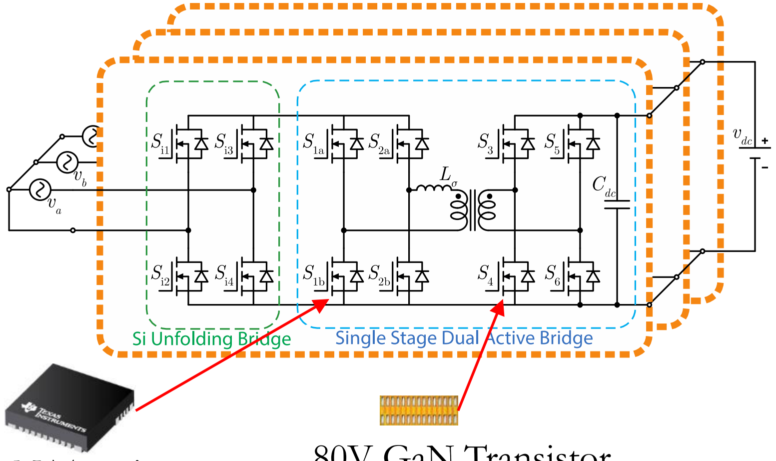
Typical Electrical Configuration of a BESS

GaN-based battery energy storage system

Project Accomplishment (2019-2022): 48V/10 kWH GaN BESS

3-phase AC Grid

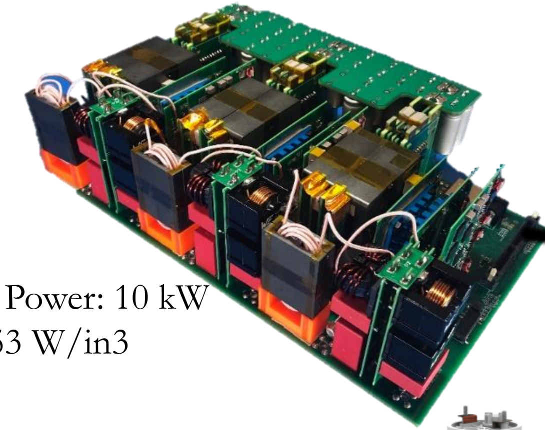
(208V or 480V)



48V battery

650V GaN Transistor

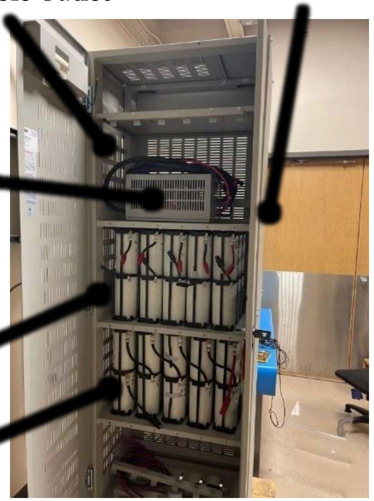
80V GaN Transistor



GaN Converter Power: 10 kW
Power density: 53 W/in3

AC cable outlet

battery cable outlet



UEP Zinc Manganese Dioxide battery

3-Phase 10kWH BESS

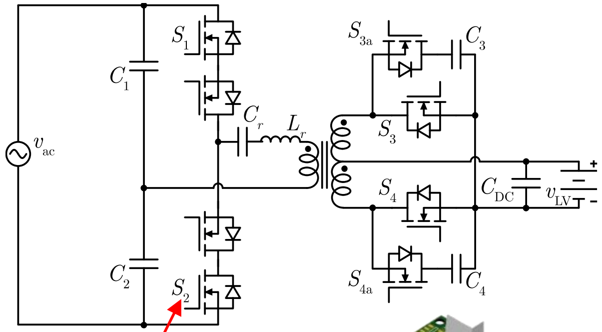
TEXAS The University of Texas at Austin SPEC

Project Goal (2021-2022): 12V/1kWH Integrated BESS (iBESS)

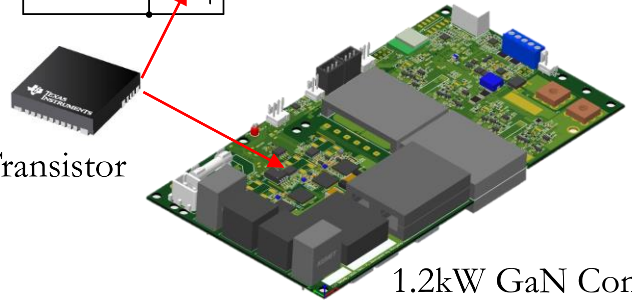
1-Phase

AC Grid

(240V)



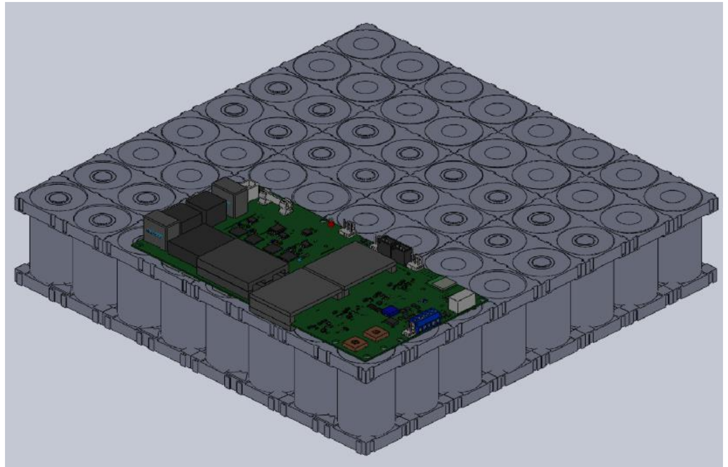
12V battery



650V GaN Transistor

1.2kW GaN Converter: 58W/in^3

1 kWH iBESS = GaN Converter+BMS+12V Battery



Size=276*276*88.6mm
Energy Density: 2.4WH/in^3

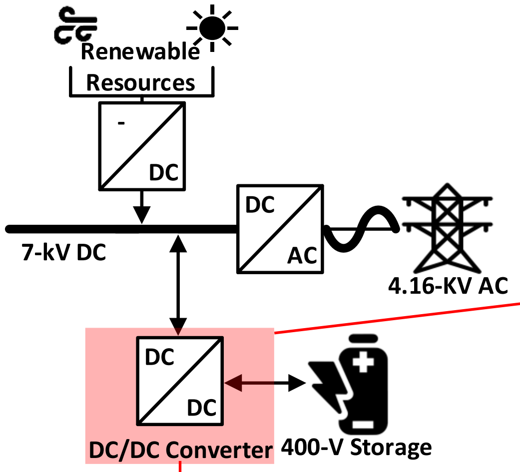
Medium voltage storage PE using SiC-based converter

- Background
  - Facilitate large-scale energy storage to improve resiliency and modernize the power grid.
  - Improve energy storage performance using wide bandgap SiC devices.
- Benefits
  - A hybrid topology of MMC and dual-active bridge is proposed. The proposed circuit can achieve lower submodule switching frequency compared with medium-frequency transformer frequency ($MMC\ f_{SW} = 1/3 \times f_{transformer}$), and high voltage step-down ratio from the medium voltage side to the transformer ($MMC\ step\ down$ ratio $= 10$).
- Challenges
  - Lack of inexpensive commercially available SiC devices above 3.3 kV.
  - Testing higher voltage WBG devices for application reliability.

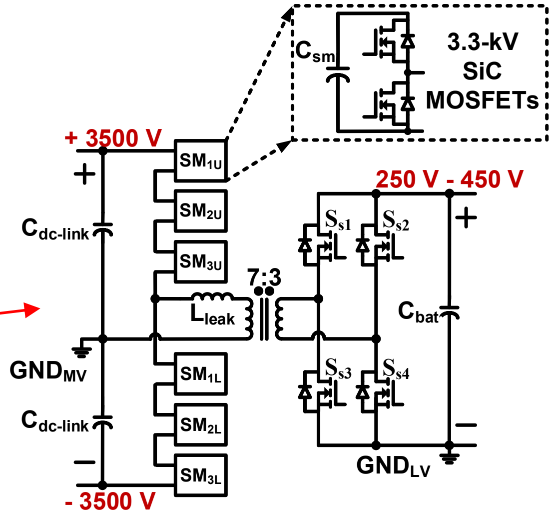
THE OHIO STATE UNIVERSITY

HPPE Center for High Performance Power Electronics

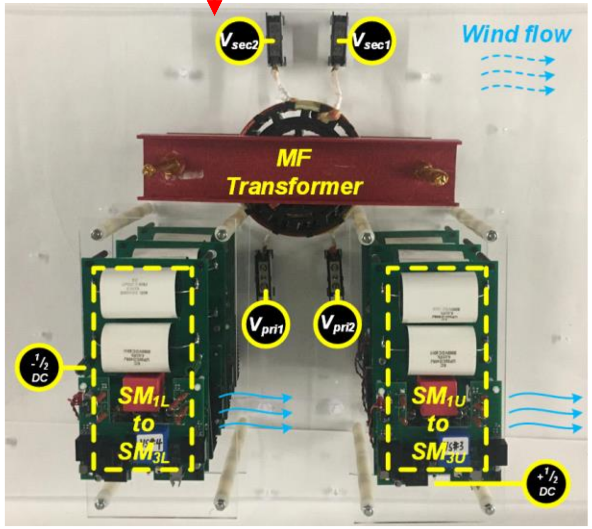
GeneSiC SEMICONDUCTOR



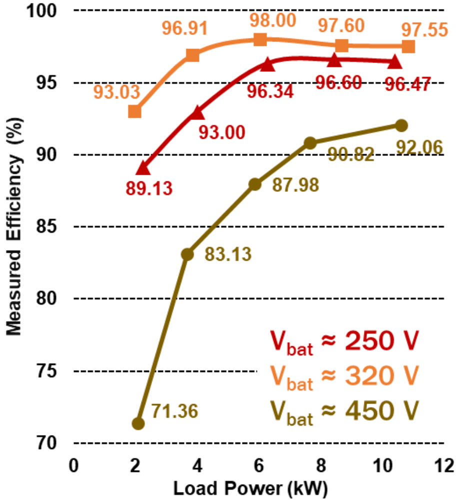
MVDC based renewable energy harvesting system with storage



Proposed MMC-based dc/dc converter



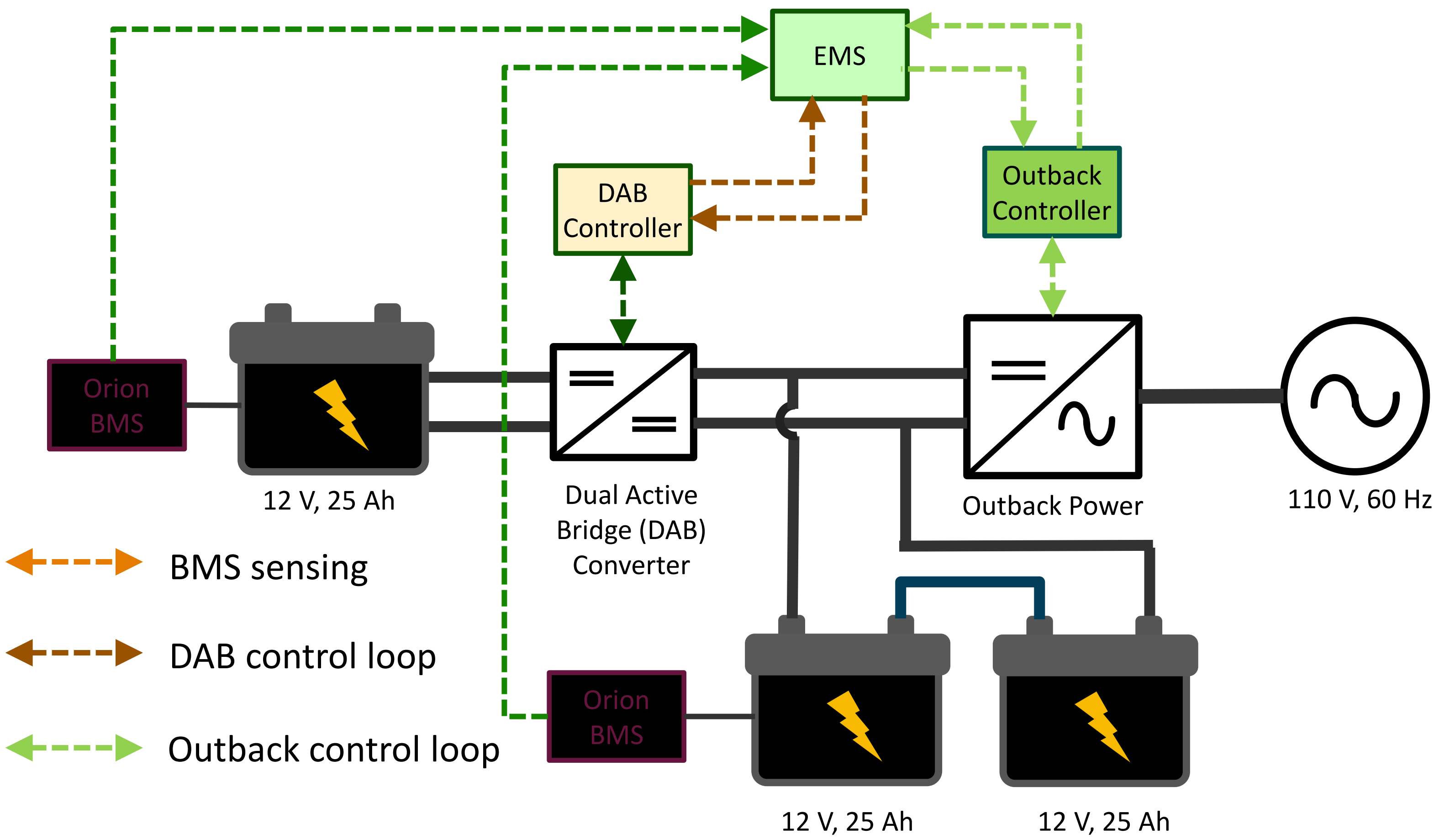
7-kV to 400-V dc/dc converter prototype (MMC & 60-kHz transformer)



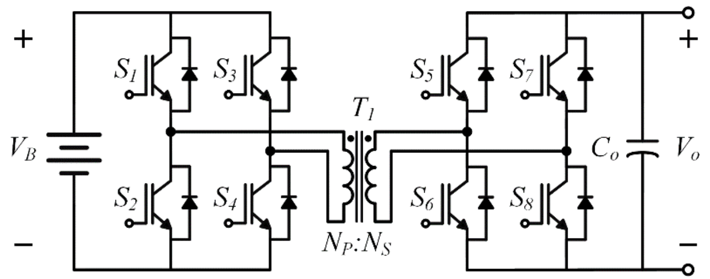
Measured converter efficiencies at different battery voltages.

Application of a dual-active bridge converter in the control of hybrid systems

One stack with 2 12 V batteries in series in parallel with a stack with a DAB controller and 1 12 V battery
Control the system to make sure that all 3 12V batteries are charged and discharged at the same rate



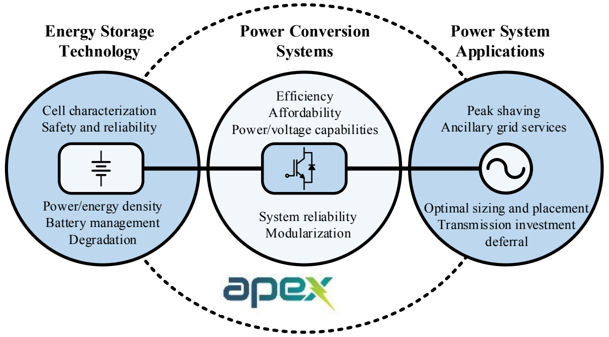
Jacob Mueller, et al. APEX Lab (SNL)



Integration of power electronics and components research at Sandia

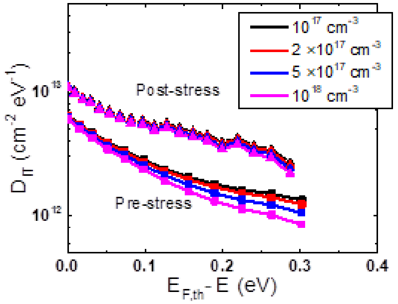
Advanced Power Electronics Conversion Systems Laboratory

- R&D of new power conversion topologies and intelligent control strategies; leverages capabilities of advanced components and materials, verifies performance through hardware experimentation



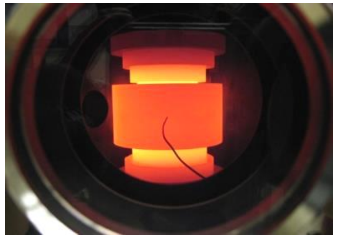
Wide Bandgap Semiconductor Characterization Laboratory

- Utilizes a range of techniques from atomic-scale characterization to reliability testing in switching circuits; stressing WBG power devices, measuring their change in performance, modeling the results, and ascertaining the impact on the PCS



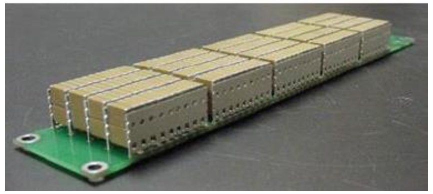
Magnetics Fabrication and Characterization Laboratory

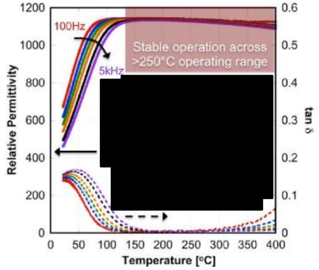
- R&D of new high magnetization, low loss magnetic cores for high frequency converters; going beyond state-of-the-art through the implementation of iron nitride, development of new low loss soft magnetic core materials capable of operating in conjunction with WBG semiconductor-based PCS



Advanced Dielectric Laboratory

- Performs reliability assessment on commercial capacitors, understands failure physics for better reliability models, and develops next-generation capacitor materials; evaluating reliability of current generation ceramic capacitors for DC-link applications; evaluates next-gen high temperature capacitors under realistic ripple waveform seen in PCS



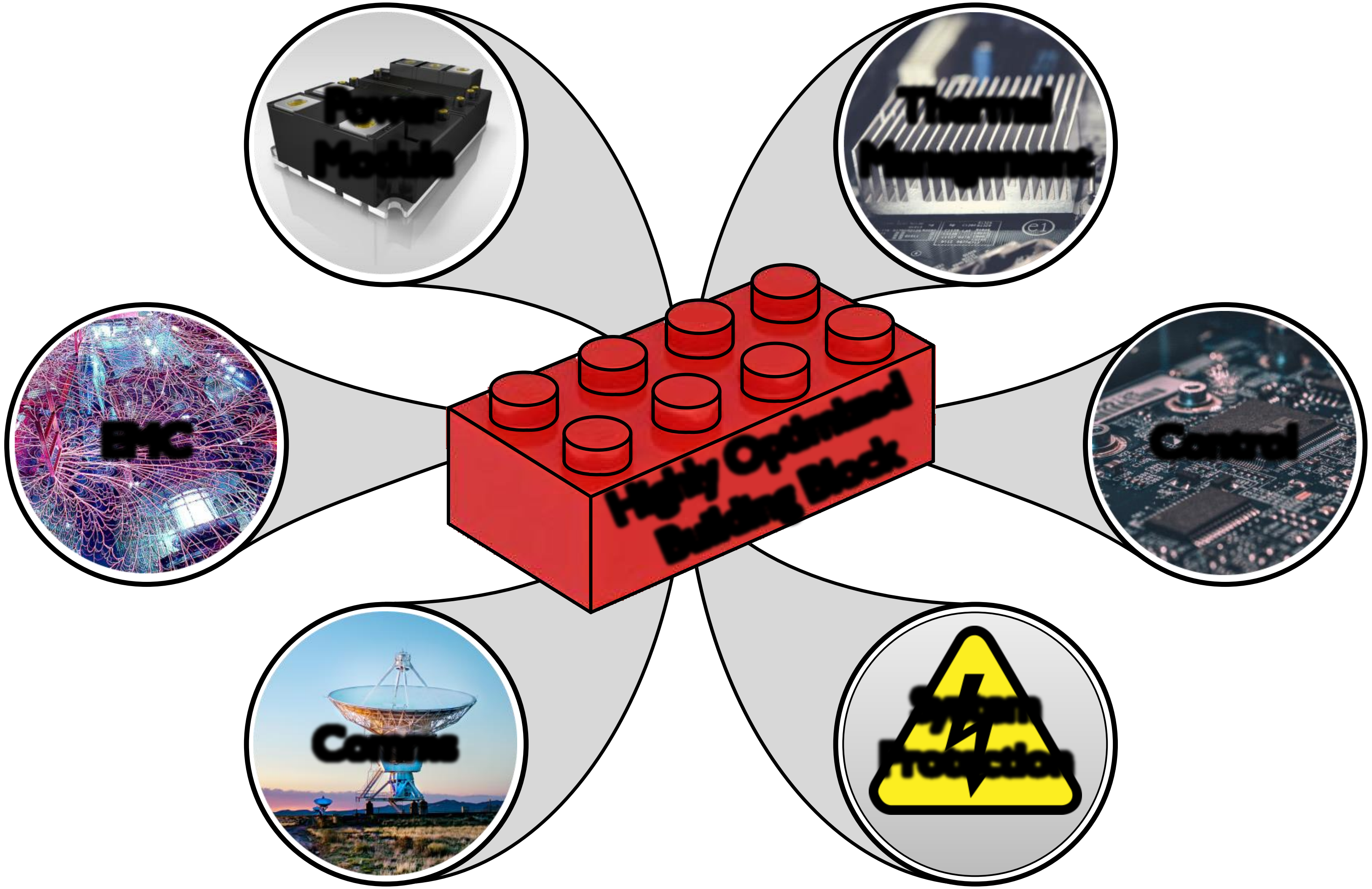


New components are important, but not the whole story

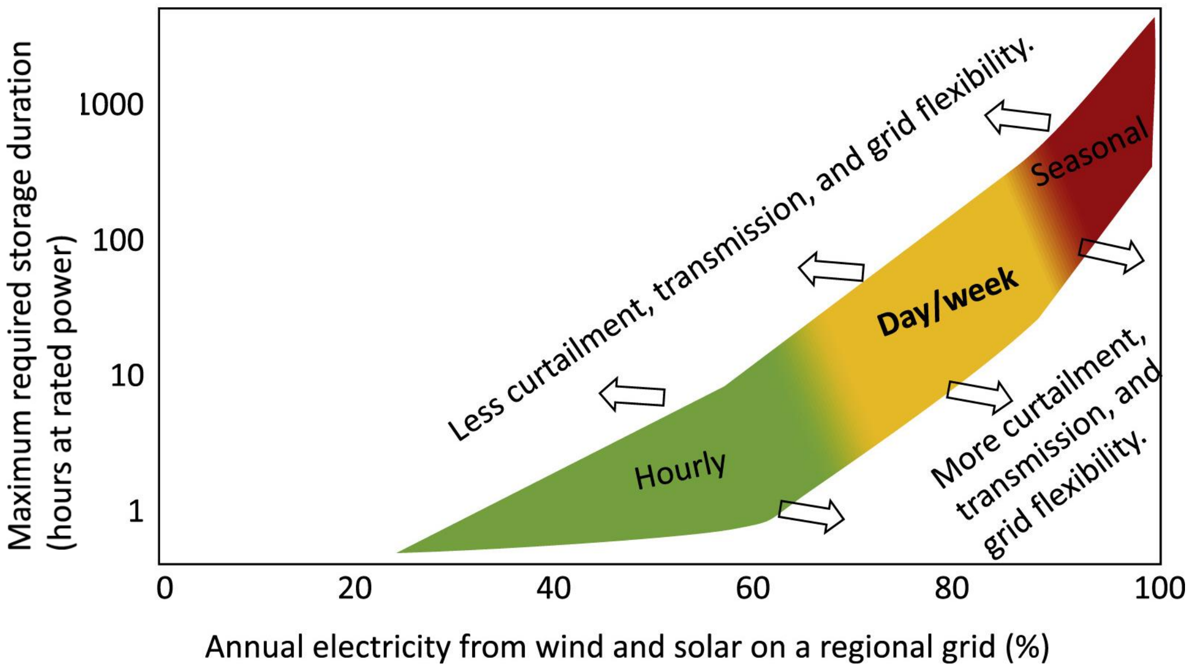
Advanced Topologies: Modular, fault-tolerant hardware architectures

Advanced Control Systems: Methods for detecting and reacting to internal failures in real time

Design-For-Reliability: Computational tools for assessing reliability and remaining time-to-failure based on application-specific operating conditions



Future outlook on the grid energy storage industry



Different energy storage technologies will be needed for different discharge durations.

Each technology will present the need for new power conversion systems.

Flow batteries (<1 day)

Hydrogen Systems (Days)

Concentrated solar (Days)

Target research areas

1. Power conversion system for hybrid scalable energy storage deployments
    - Support for ‘fast’ and ‘slow’ batteries
    - Modular topologies for direct MV grid connection
    - Integration of storage in existing and emerging power electronic energy infrastructure
2. Uninterruptible converter topologies for critical storage assets
    - Fault-tolerant and reconfigurable hardware architectures
    - Hot-swap capable converters and storage systems (Power electronics and control systems)
3. Applications of power electronics in storage system safety
    - Stranded energy extraction
    - Active and predictive response to thermal runaway
4. Integration of advanced components
    - Wide bandgap devices
    - Advanced magnetics
    - Advanced capacitors

Thank you for your interest.

The Energy Storage Power Electronics Program is supported by Dr. Imre Gyuk and the Energy Storage Program in the DOE Office of Electricity.

Stan Atcitty, Ph.D.
Email: satcitt@sandia.gov
Phone: 505-284-2701

Valerio De Angelis, Ph.D.
Email: vdeange@sandia.gov
Phone: 505-803-0370