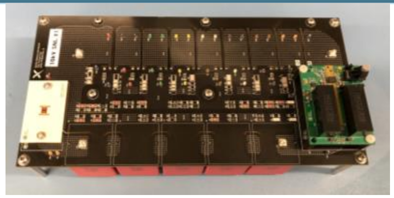
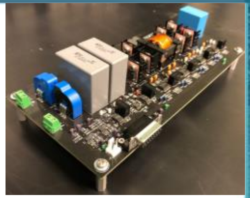
SAND2024-14258C

Sandia National Laboratories

Power Conversion and Control Systems for a Modern Electric Grid

Power Electronics R&D at Sandia National Laboratories





Jake Mueller

Center for High Performance Power Electronics (CHPPE) Annual Review

October 18th, 2024

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

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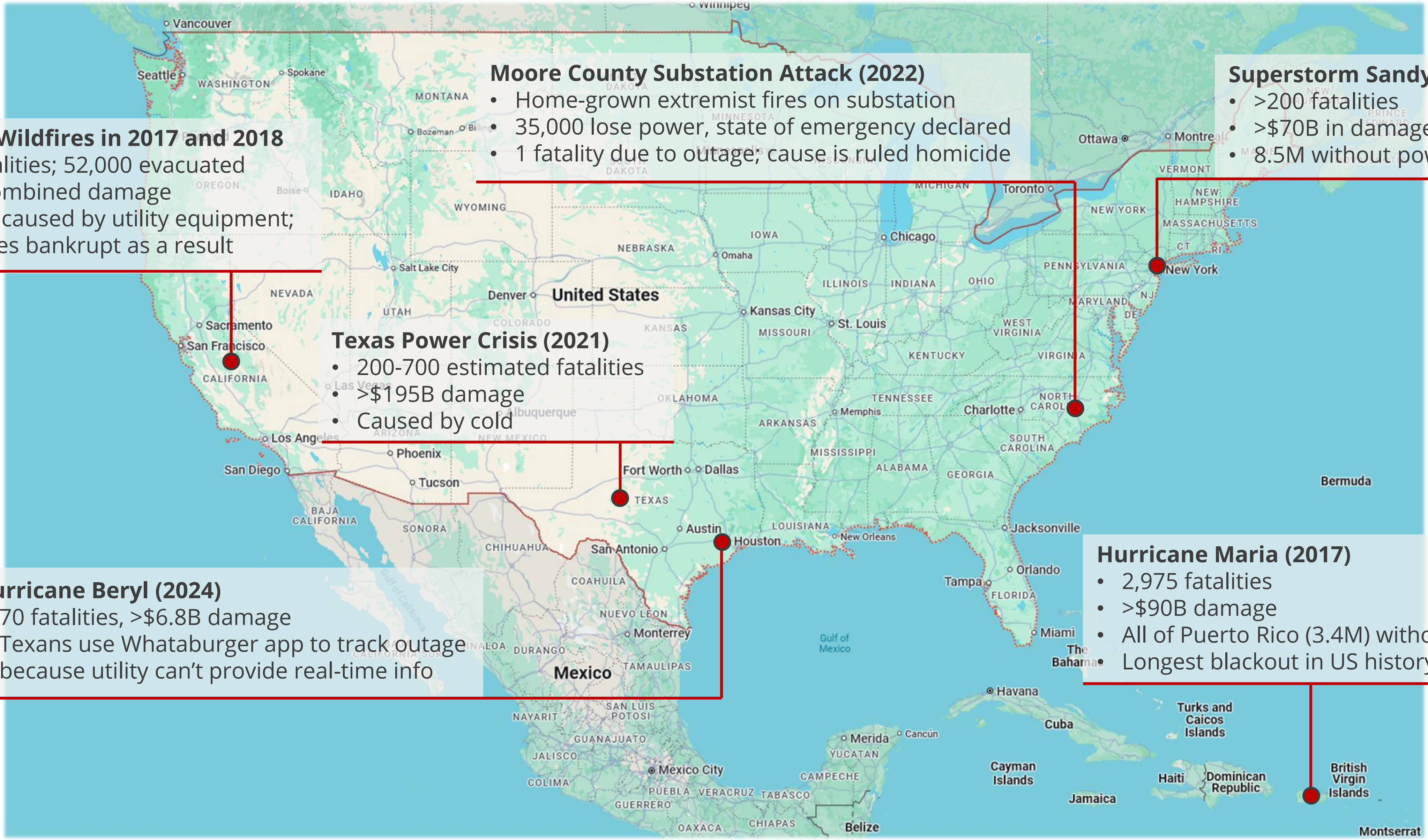
Energy Security and an Expanding Threat Space



California Wildfires in 2017 and 2018
- >100 fatalities; 52,000 evacuated
- >$25B combined damage
- Fires are caused by utility equipment; PG&E goes bankrupt as a result

Moore County Substation Attack (2022)
- Home-grown extremist fires on substation
- 35,000 lose power, state of emergency declared
- 1 fatality due to outage; cause is ruled homicide

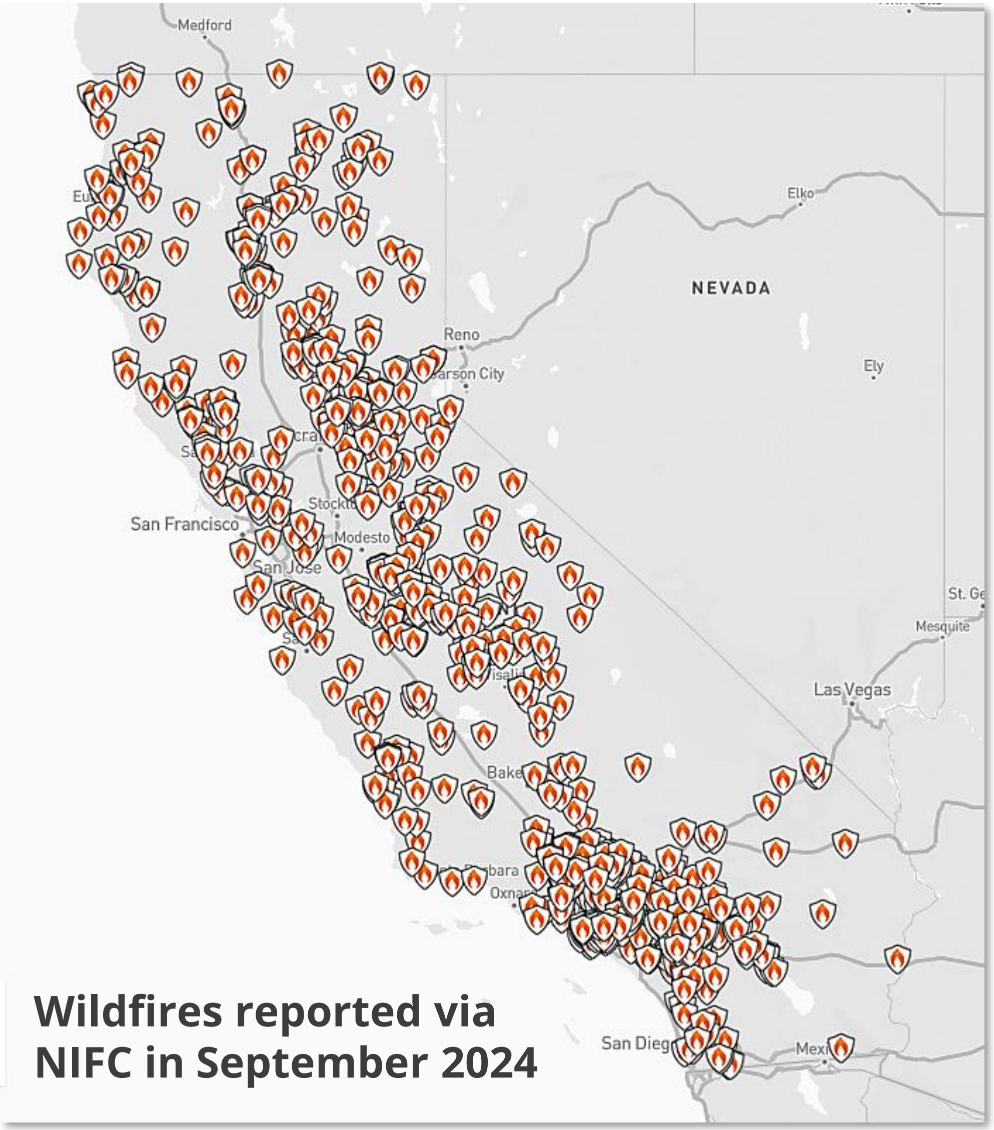
Superstorm Sandy (2012)
- >200 fatalities
- >$70B in damage
- 8.5M without power

Texas Power Crisis (2021)
- 200-700 estimated fatalities
- >$195B damage
- Caused by cold

Hurricane Maria (2017)
- 2,975 fatalities
- >$90B damage
- All of Puerto Rico (3.4M) without power
- Longest blackout in US history

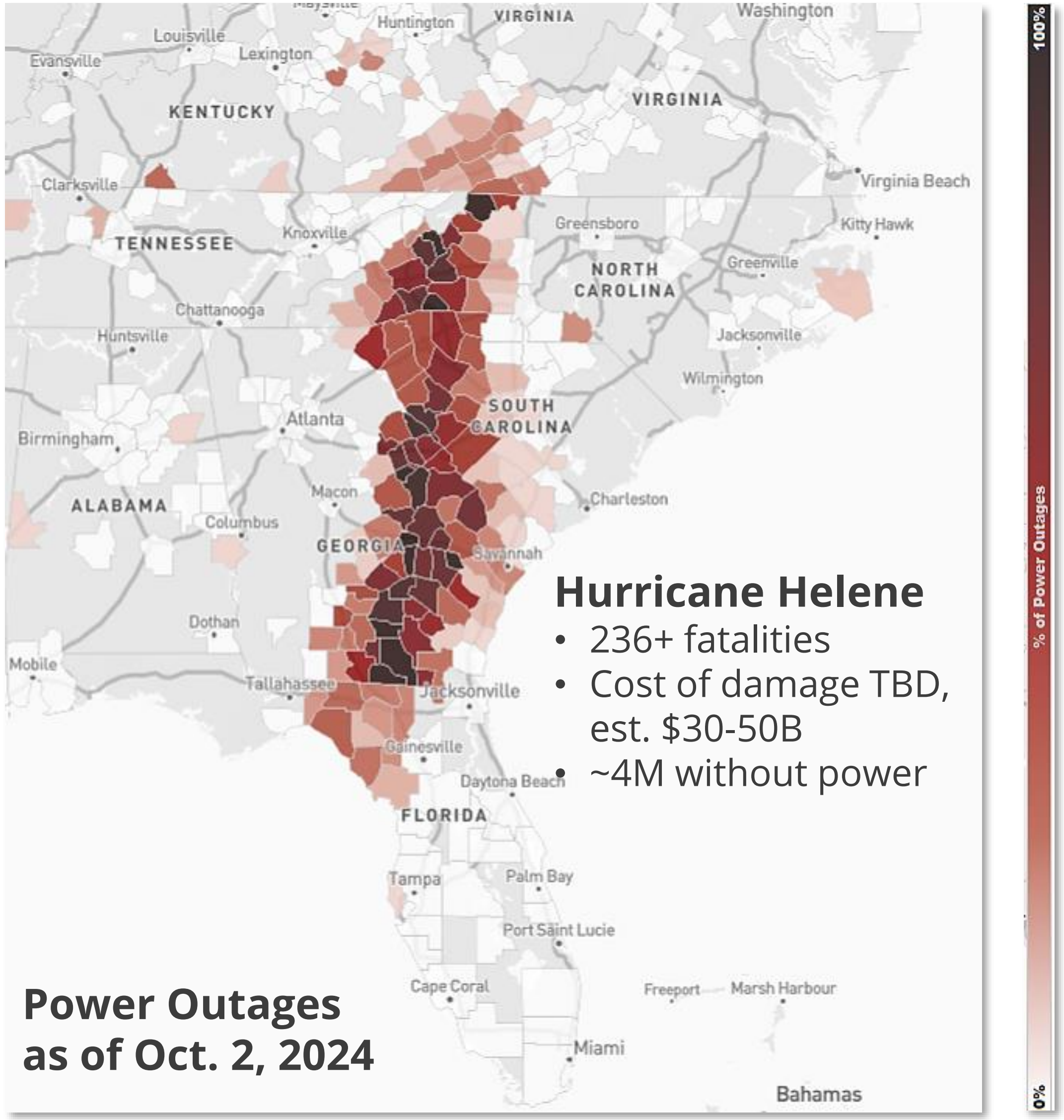
Hurricane Beryl (2024)
- 70 fatalities, >$6.8B damage
- Texans use Whataburger app to track outage because utility can't provide real-time info

Current Events in Energy Security



Wildfires reported via NIFC in September 2024

Source: https://data.usatoday.com/wildfire-history



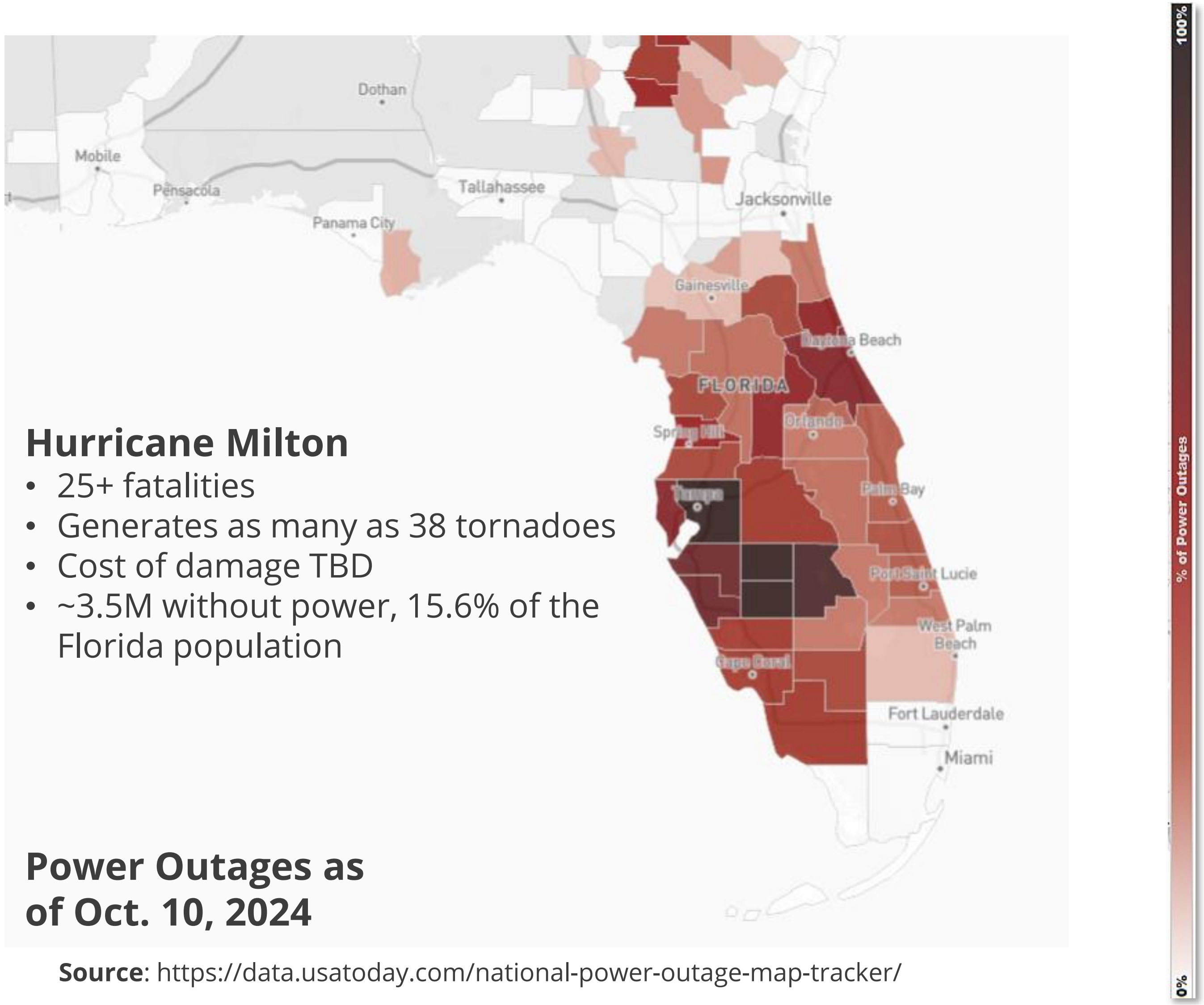
Hurricane Helene

- 236+ fatalities
- Cost of damage TBD, est. $30-50B
- ~4M without power

Power Outages as of Oct. 2, 2024

Source: https://data.usatoday.com/national-power-outage-map-tracker/

Even More Current Events in Energy Security



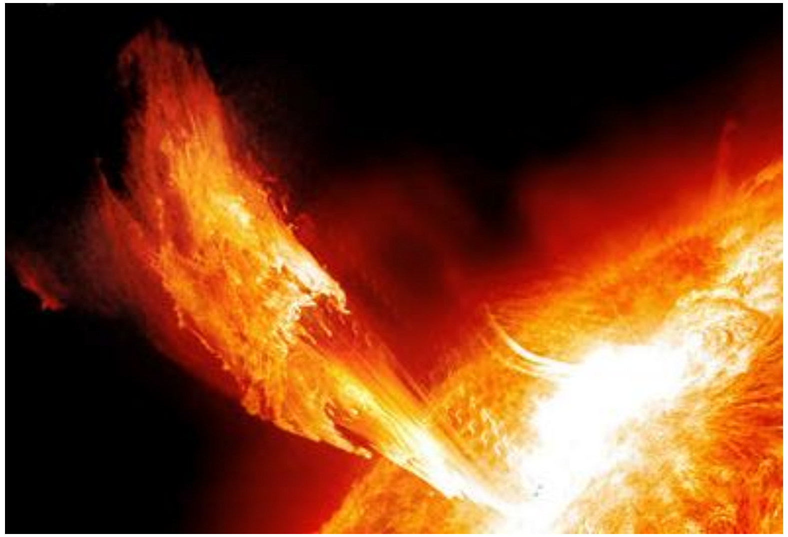
Hurricane Milton

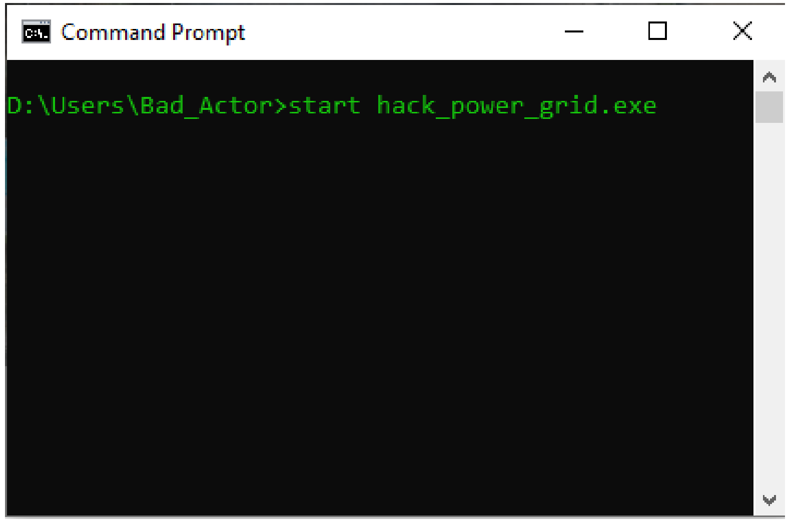
- 25+ fatalities
- Generates as many as 38 tornadoes
- Cost of damage TBD
- ~3.5M without power, 15.6% of the Florida population

Power Outages as of Oct. 10, 2024

Source: https://data.usatoday.com/national-power-outage-map-tracker/

Meeting the Needs of Grid Modernization

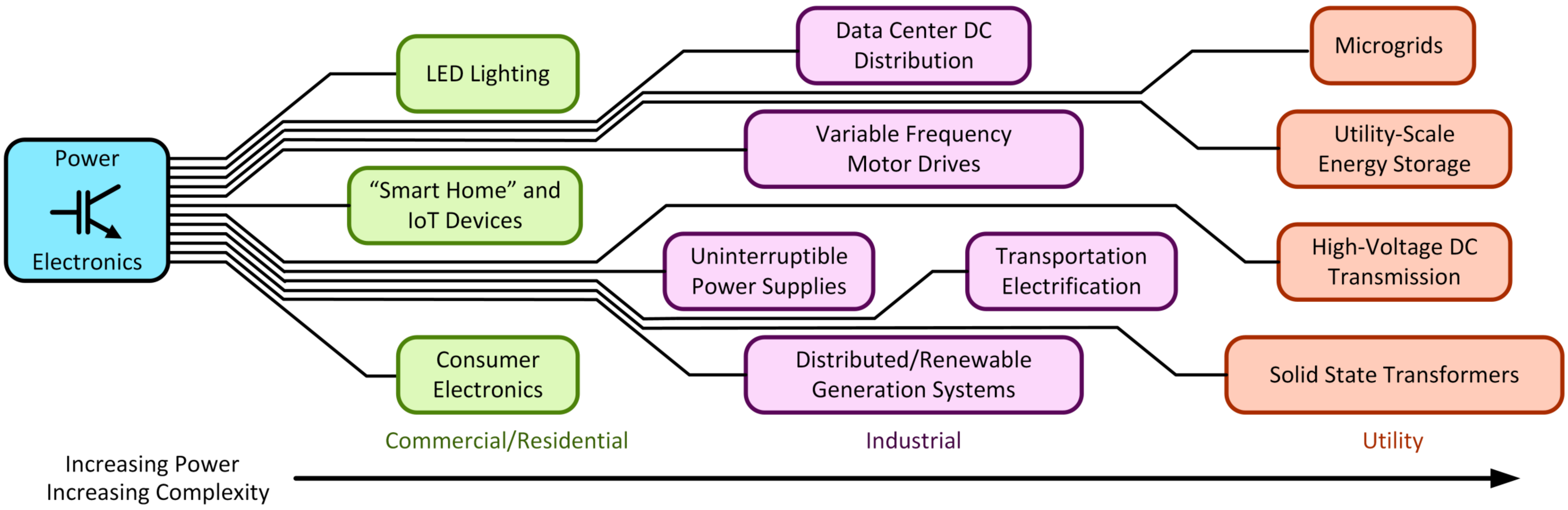




Power Electronic Solutions

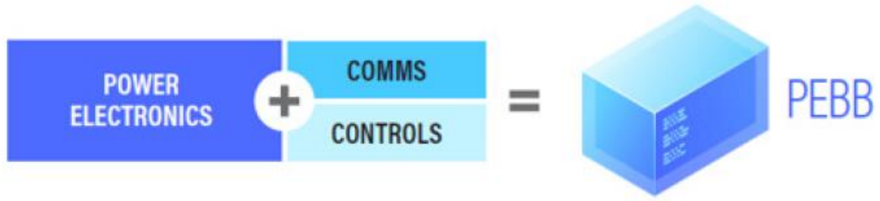
Power electronics provide **two critical functions**:

1. Efficient **conversion** between disparate forms of electricity
2. Unprecedented **control** over the flow of electrical energy

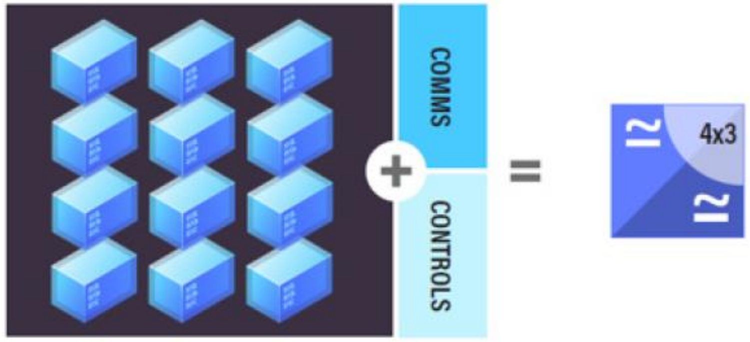


Power Electronics as Utility Infrastructure

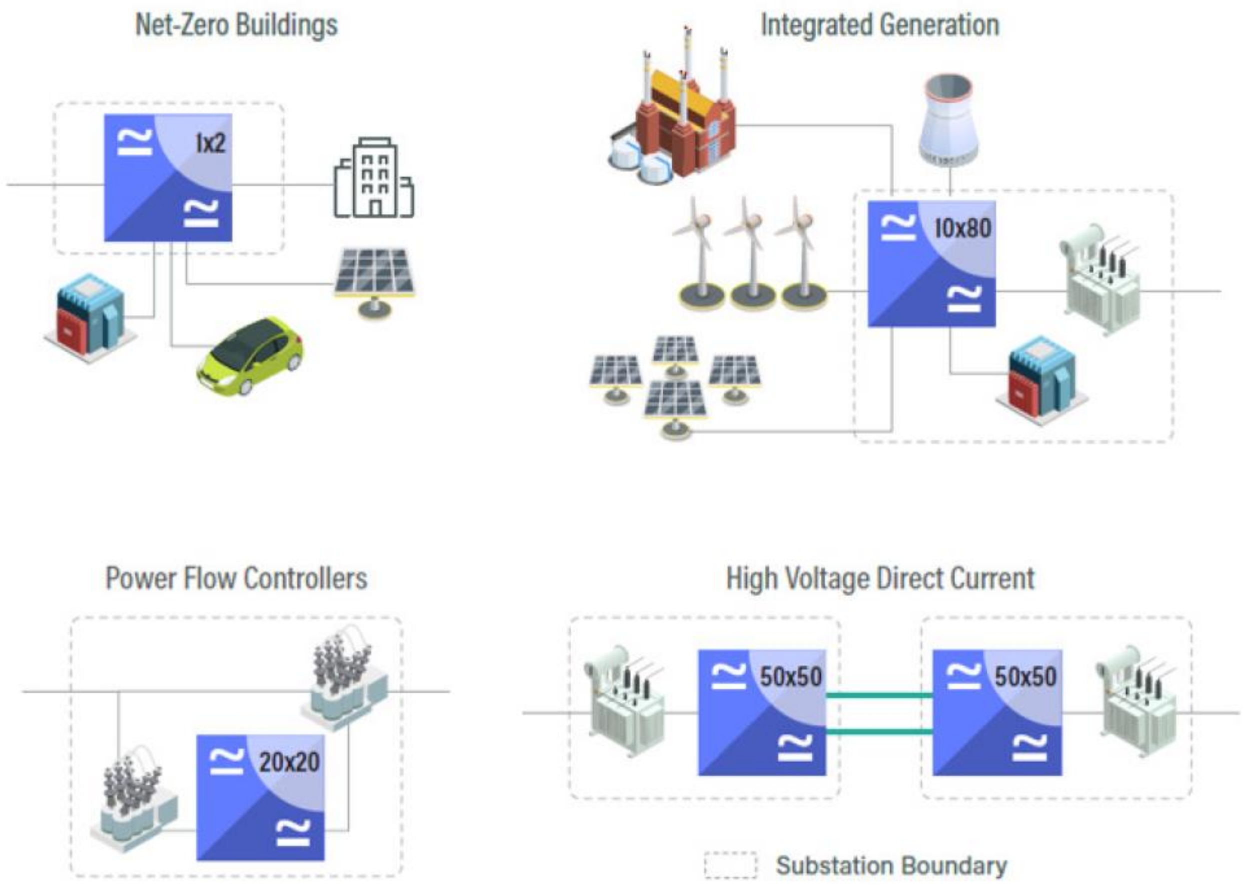
SSPS Power Electronic Building Block (PEBB)



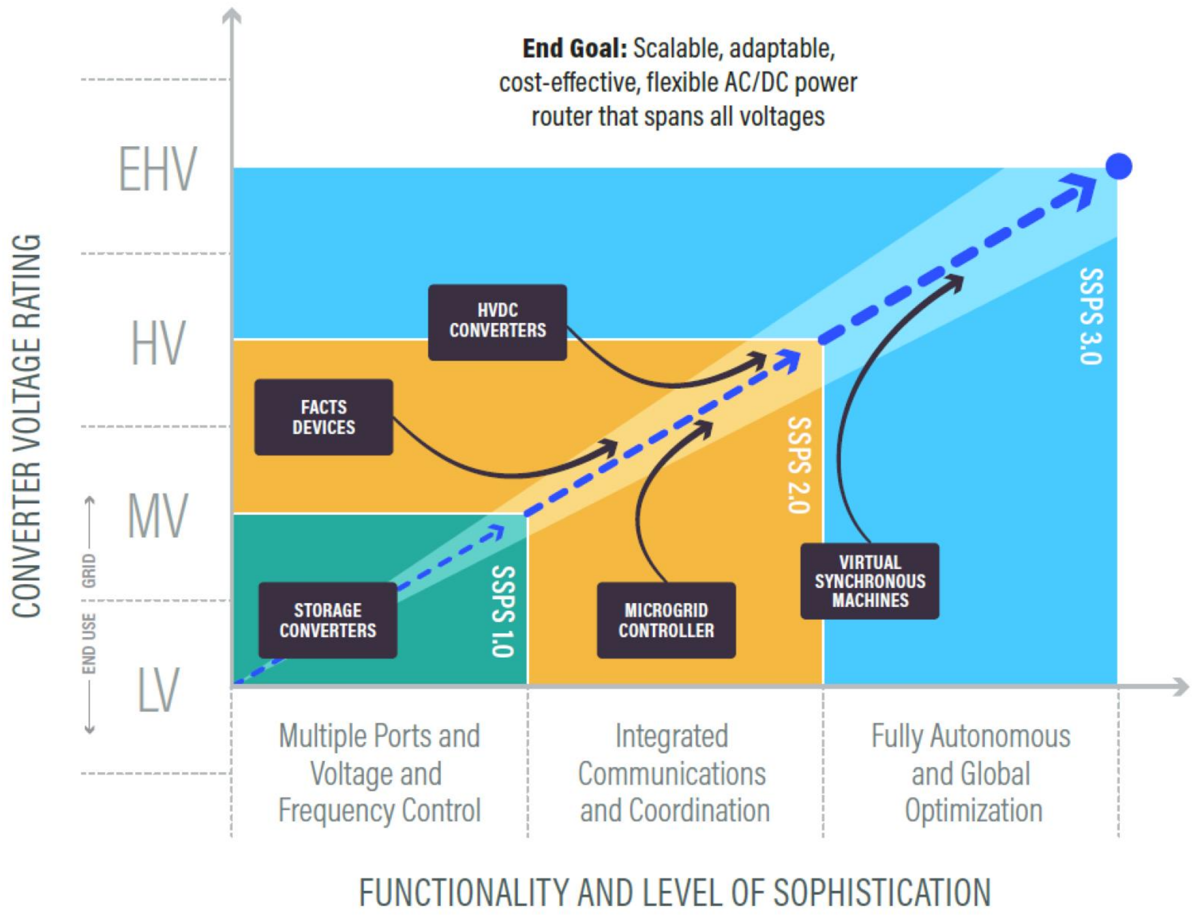
SSPS Converter

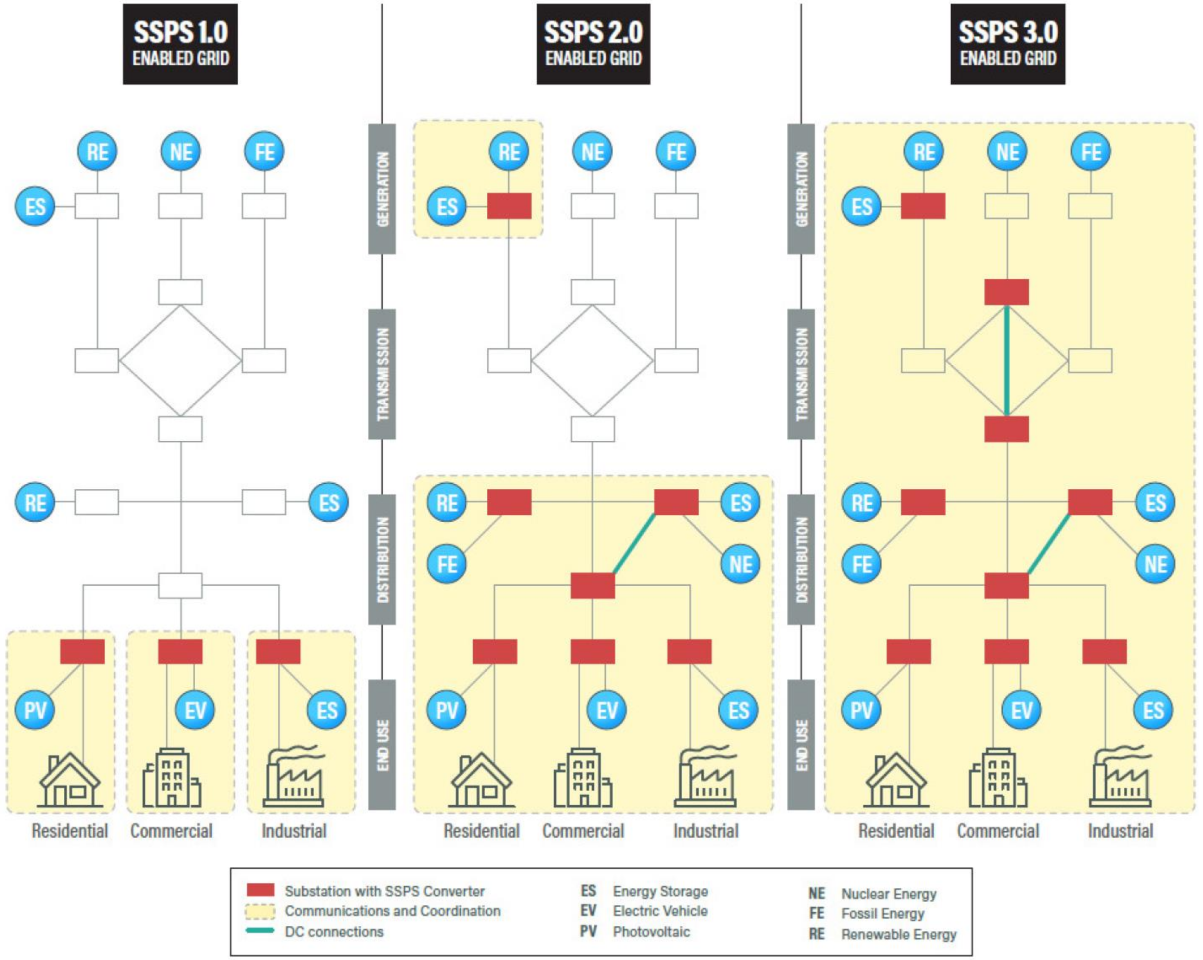


SSPS Converter Applications within Substations



Solid-State Power Substations – OE/TRAC Vision





Performance Targets

2013 ONR Naval Power Systems Technology Development Roadmap

	Near-Term (5-10 years)	Mid-Term (10-20 years)	Far-Term (20-30 years)
Efficiency	98%	>98%	>98%
Power Density	1.25 MW/m^3	2 MW/m^3	3 MW/m^3

2017 US DRIVE Electrical and Electronics Technical Team Roadmap

	2020 Target	2025 Target
Traction Motor Drive Density	4 MW/m^3	33 MW/m^3
Power Inverter Module Density	13.4 MW/m^3	100 MW/m^3
On-Board Charger Efficiency	97%	98%
On-Board Charger Power Density	3.5 MW/m^3	4.6 MW/m^3
DC-DC Converter Efficiency	>94%	98%
DC-DC Converter Power Density	>3 MW/m^3	4.6 MW/m^3

2020 DOE/OE TRAC Program Solid State Power Substation Roadmap

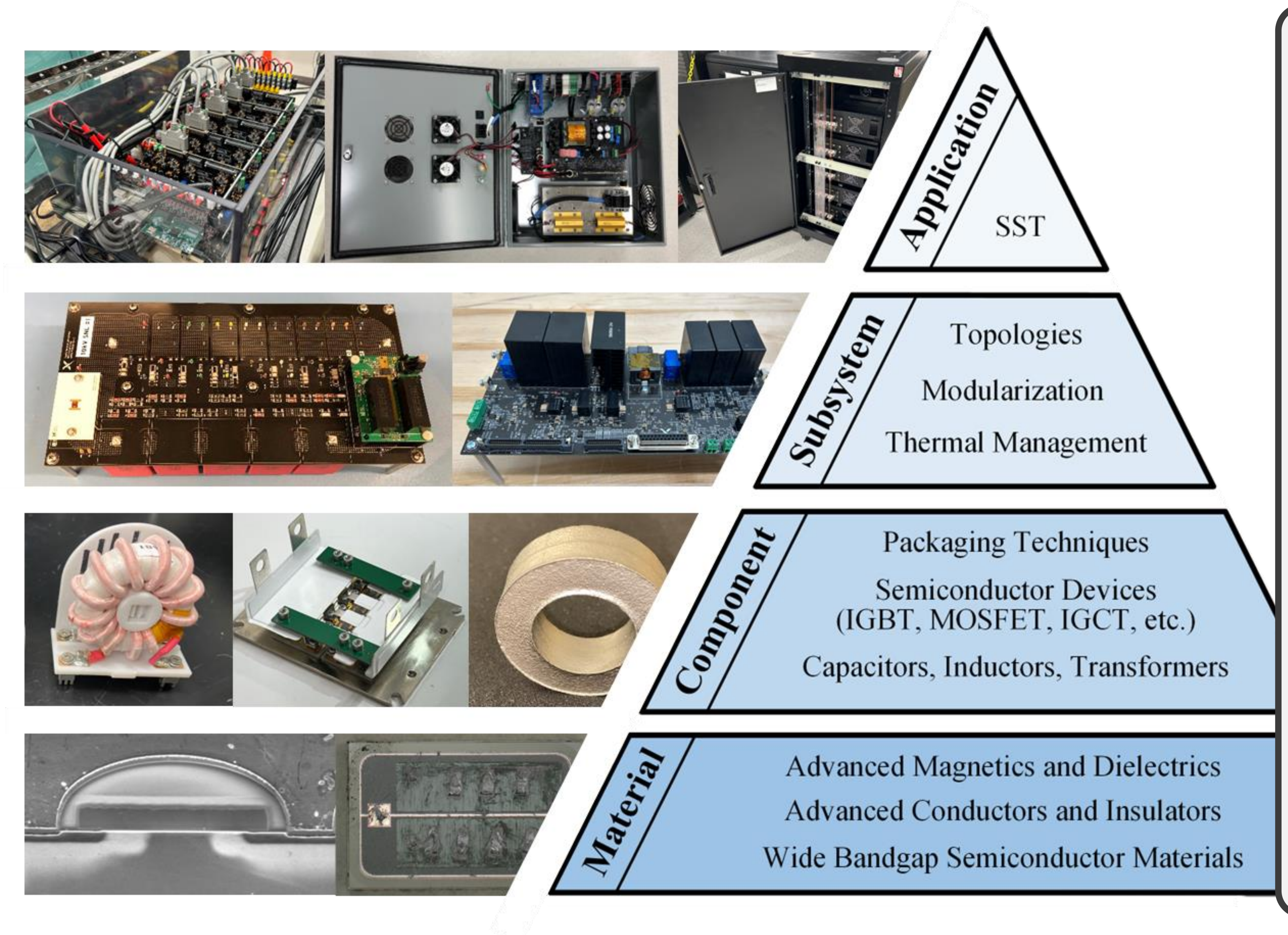
		SSPS 1.0 UP TO 34.5 KV UP TO 10 MVA	SSPS 2.0 UP TO 138 KV UP TO 100 MVA	SSPS 3.0 ALL VOLTAGES ALL POWER LEVELS
GOALS	**R&D Challenges**	**Goals**		
SUBSTATION APPLICATION	Converter System Cost and Performance	< \$150/kVA > 96% 2 MW/m^3 10-Year Mean-Time-to-Failure (MTTF)	< \$125/kVA > 96.5% 5 MW/m^3 20-Year MTTF	< \$100/kVA > 97% 10 MW/m^3 40-Year MTTF
CONVERTER BUILDING BLOCK	Block/Module Cost and Performance	< \$20/kVA > 97% 5 W/cm^3 2-Year MTTF	< \$15/kVA > 98% 10 W/cm^3 4-Year MTTF	< \$10/kVA > 99% 20 W/cm^3 8-Year MTTF
	Drivers and Power Semiconductors	≥ 1.7 kV \$0.10/kW	≥ 3.3 kV \$0.10/kW	≥ 10 kV \$0.10/kW
	Dielectric, Magnetic, and Passive Components	160 kV/mm 0.1 H/m $6.0x10^7$ S/m	600 kV/mm 1.0 H/m $1x10^8$ S/m	2000 kV/mm 2.0 H/m $1.5x10^8$ S/m
	Packaging and Thermal Management	> 500 $W/(m^2°C)$	> 1000 $W/(m^2°C)$	> 10,000 $W/(m^2°C)$

The critical path for power electronics technology development in all applications includes **aggressive power density targets**

Current trend is higher voltage + higher power capacity + smaller physical size

For grid applications, **scalability is king**; no upper limit on power and voltage targets for utility-scale power conversion

Power Electronics R&D at Sandia



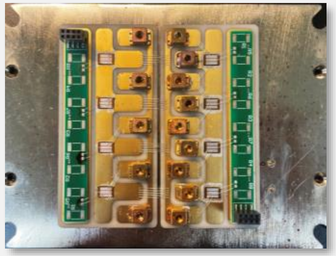
Power Electronics Lab Spaces Focused on Grid Modernization

Medium Voltage Power Conversion Facility

DETL: Distributed Energy Technologies Laboratory

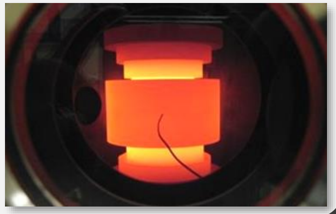
APEX: Advanced Power Electronic Conversion Systems Laboratory

ESCAL: Energy Storage Control and Analytics Lab



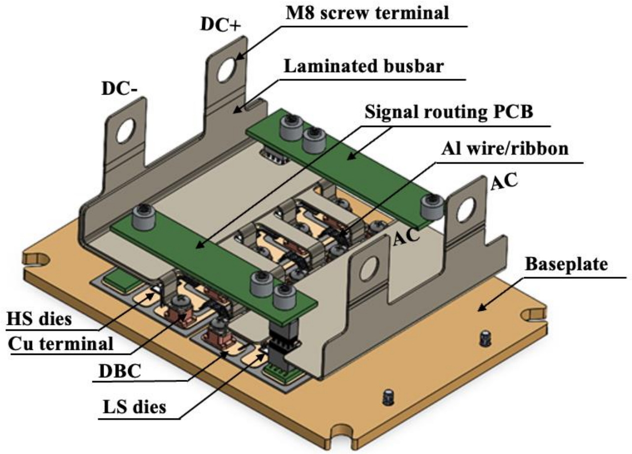
PEAK: Power Electronics Advanced Packaging Lab

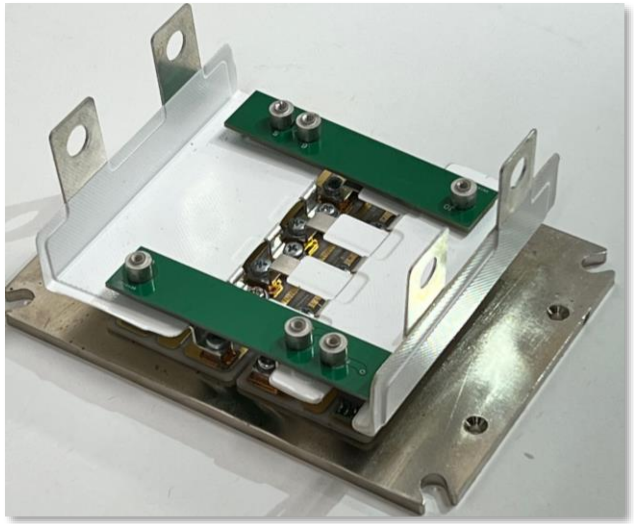
Various Device/Material Characterization Labs



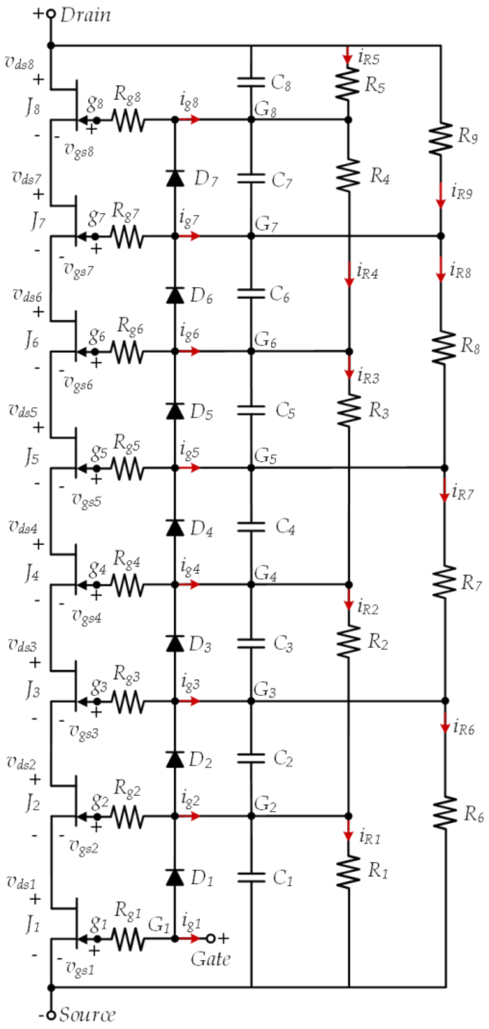
Power Electronics at Medium Voltage (and Beyond)

Power Component Innovations

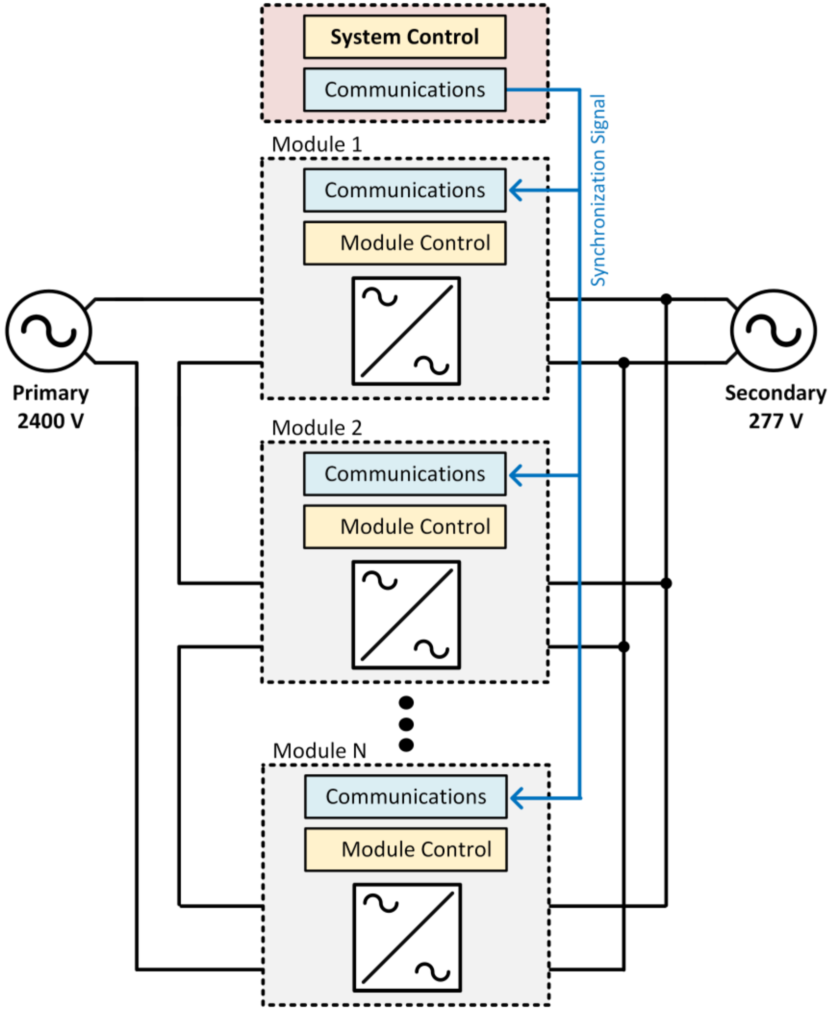




Advanced Circuits and Topologies



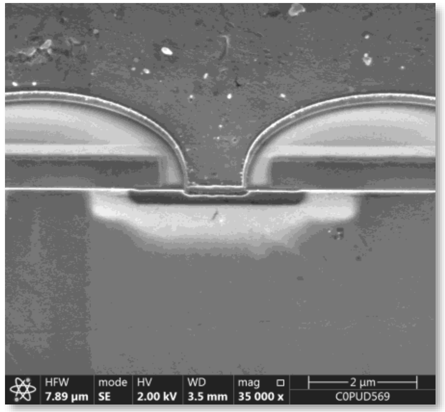
Modular System Architectures



Medium Voltage Semiconductors

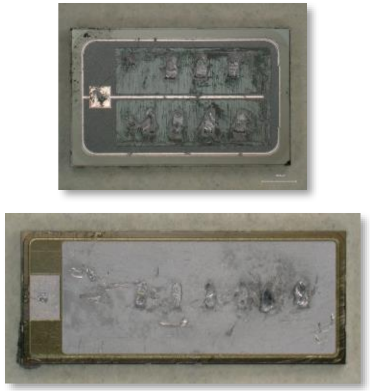
- 3.3kV SiC MOSFETs are now commercially available from a fair variety of manufacturers
- Questions remain regarding device reliability in practical field conditions
- Accelerated Lifetime Testing via H3TRB
  - 85°C, 85% rH, 1100 hours
  - 20%/40%/60%/80% of rated voltage
  - Full electrical characterization performed at t = [0, 100, 300, 700, 1100] hours
- Device population includes discrete and power module form factors from 5 manufacturers
- Reliability evaluation is part of the Medium Voltage Resource Integration Technologies (MERIT) project sponsored by the Grid Modernization Lab Consortium

SCM Imaging



3µm

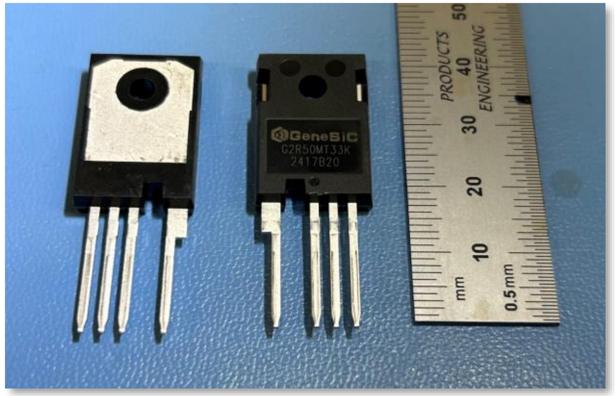
Bare Die



5mm

Discrete Device

TO-247, TO-263



25mm

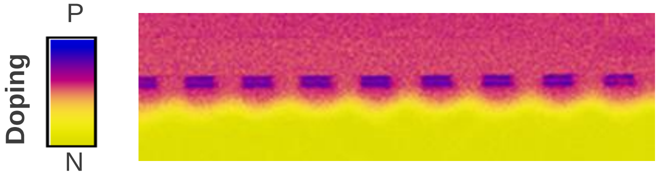
Power Module

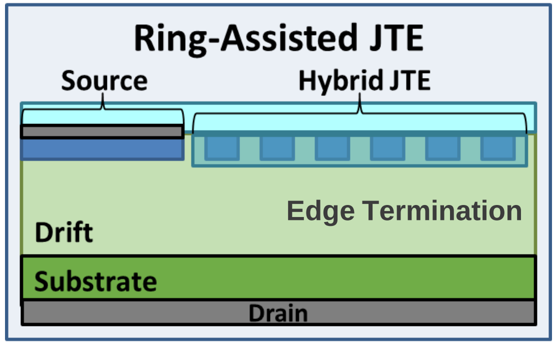
XHP3, LV100, LM3, LinPak

60mm

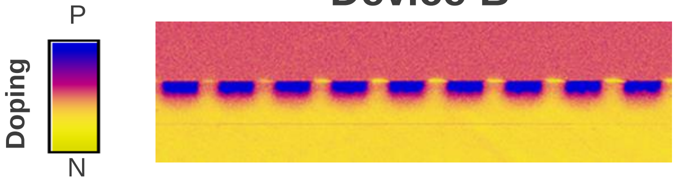
Explaining Differences in Degradation

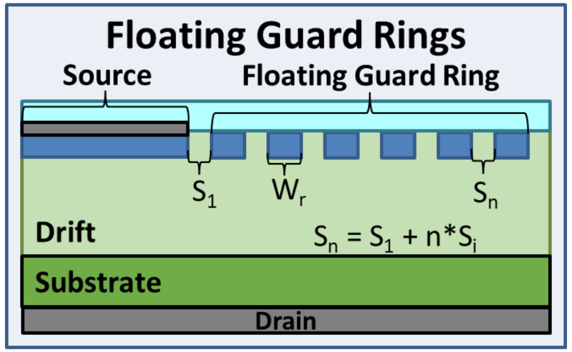
Device A

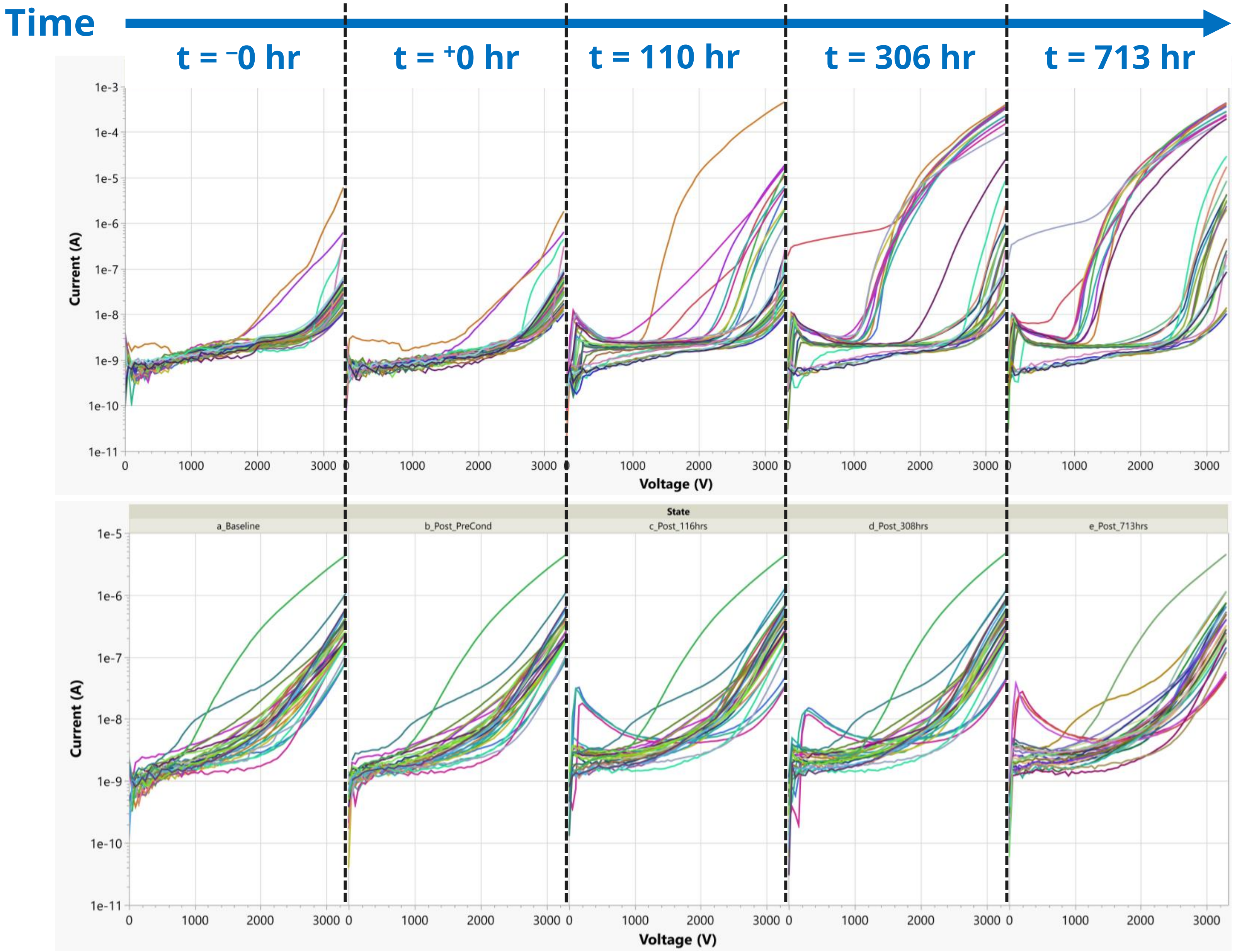




Device B





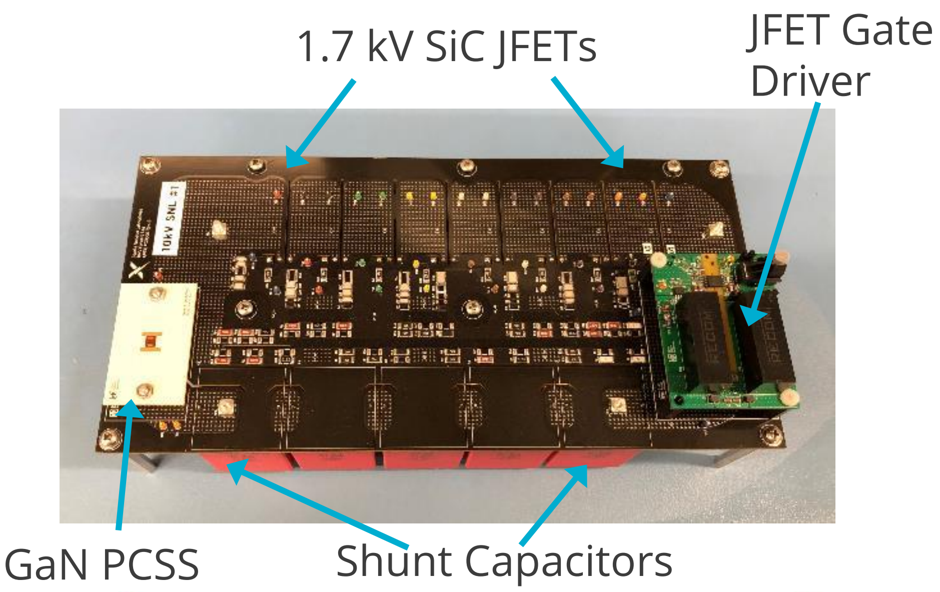


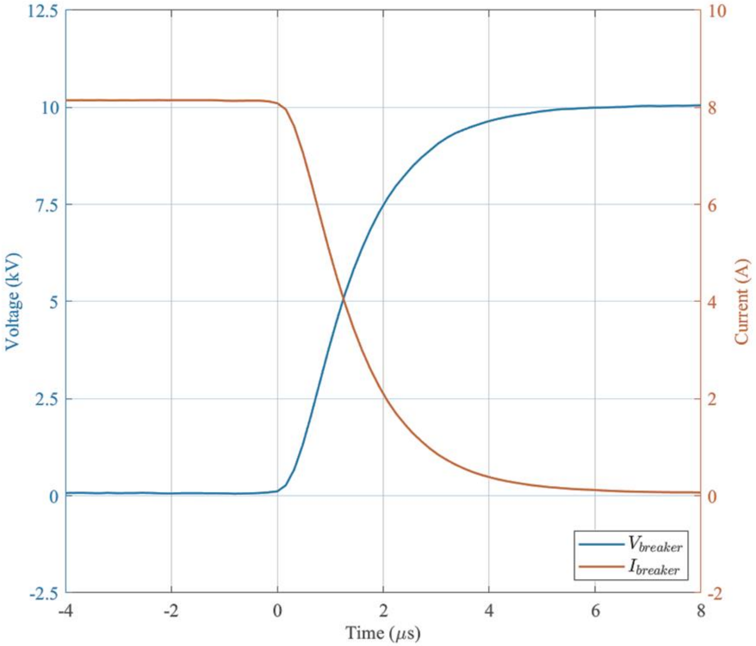
Solid-State DC Circuit Breaker

- Cascaded JFET switch topology with passive balancing network to distribute voltage stress
- Normally-On JFETs with low on-resistance and low auxiliary drive loss
- Normally-Off photoconductive semiconductor switch (PCSS) that triggers immediately after a fault to shunt current
- Capacitor for absorbing + dissipating energy from flyback current

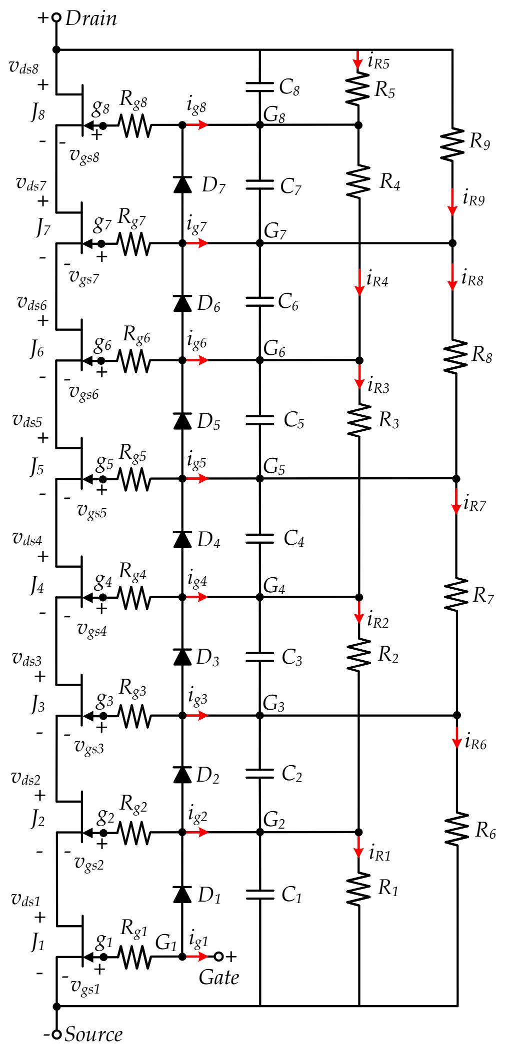
Performance Targets

Parameter	Requirement
Operating Voltage	10kVDC
Rated Power	1MW
Efficiency	99.97%
Response Time	< 500μs
Operating Life	30,000 cycles
Power Density	> 60MW/m³





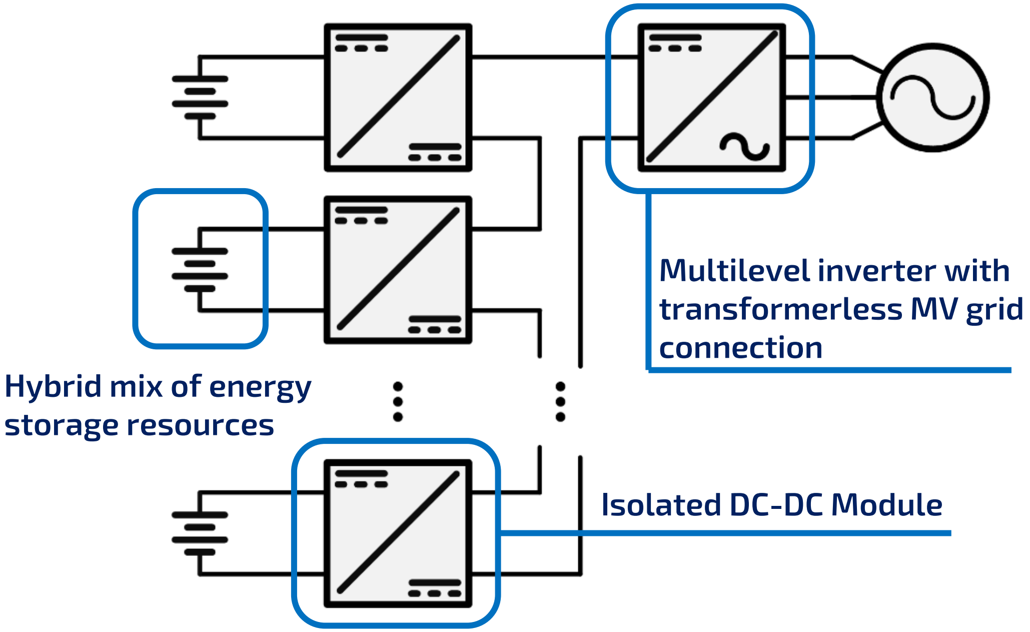
Cascaded JFET Circuit

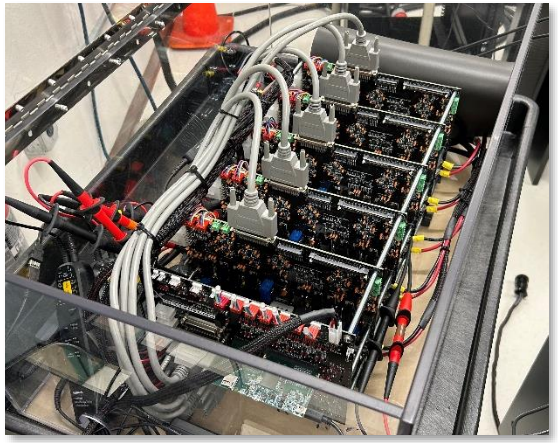


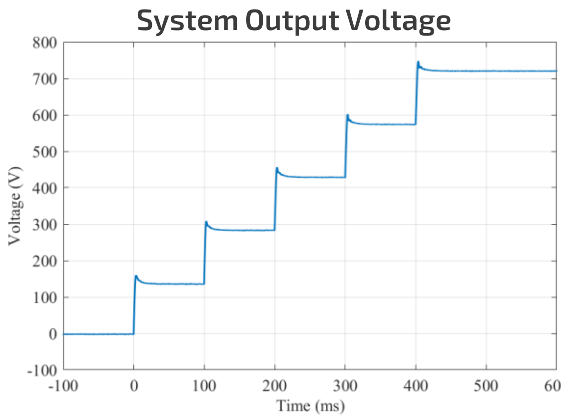
Modular Power Conversion Systems for MV Storage

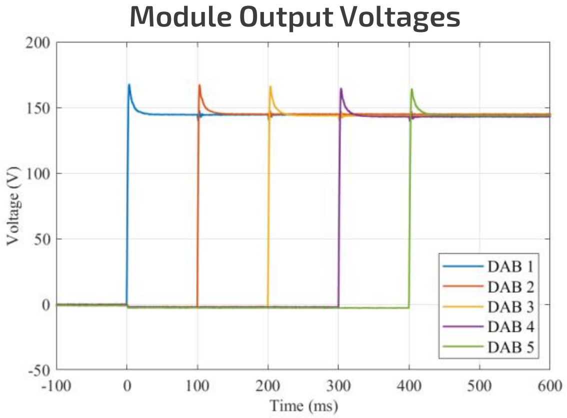
- **Challenge:** Inherently low-voltage/high-current storage devices must interface with high-voltage/low-current power systems
- Power electronics must provide voltage scaling, isolation, and individual control over energy storage assets
- Higher working voltage means lower power loss ($P = I^2R$)
- Conventional grid-tied storage is limited to working voltages on the order of 1000V DC and 480V AC

- **Goal**: Connect low-voltage storage resources directly into medium voltage grids using modular power electronics; eliminate line-frequency transformer
- Isolated DC-DC converter building blocks modules connected in series/parallel arrangements for exceptionally high voltage gain

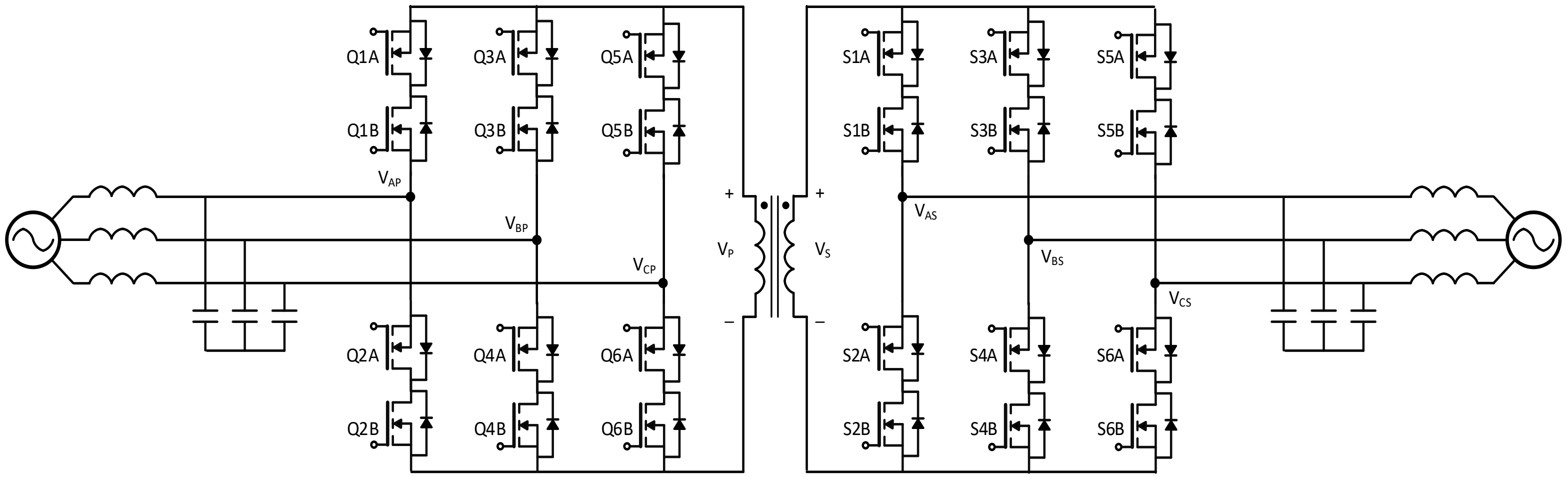




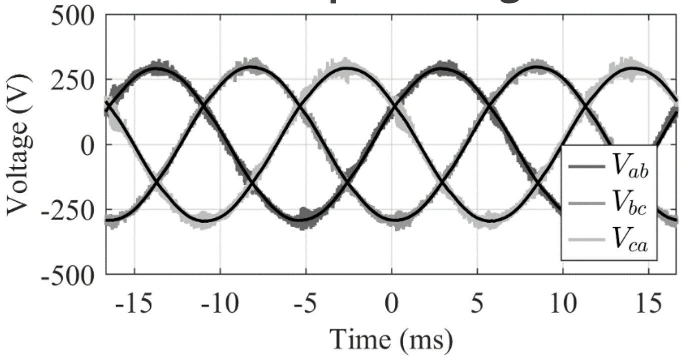




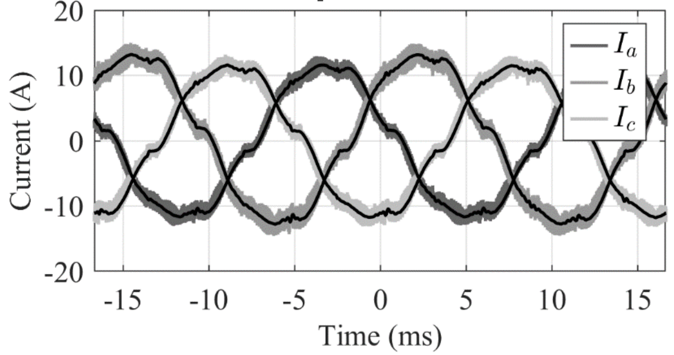
Direct AC-AC Solid State Transformer



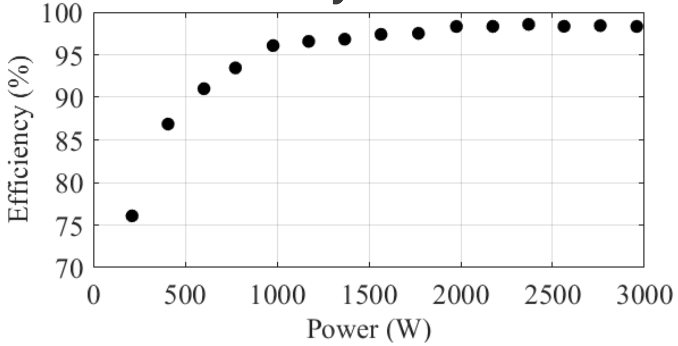
AC Output Voltage



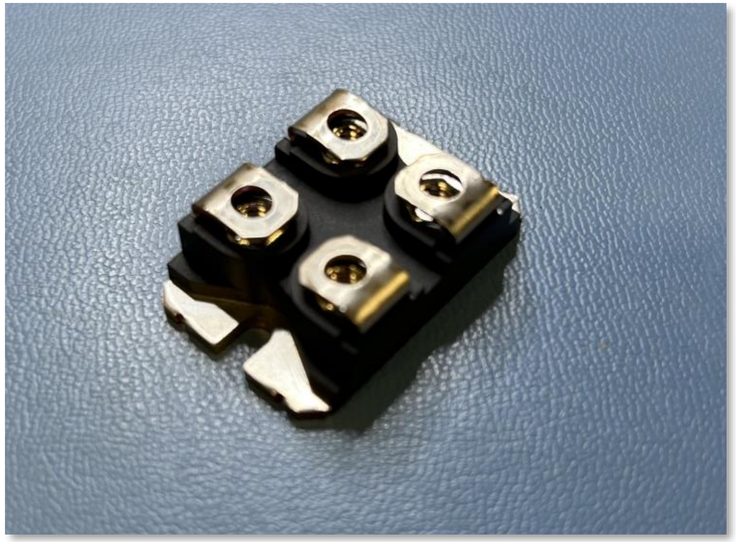
AC Output Current



Efficiency vs. Power



Rack-Based Converter Module



Monolithic 1.2kV SiC Bidirectional Field Effect Transistors (BiDFETs)

Thanks For Your Attention

This work was supported by the US DOE
Office of Electricity Energy Storage Program
and the Grid Modernization Lab Consortium

For further information, please contact:

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