# Proceedings
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# National Institute of Standards and Technology (NIST)
# High Megawatt Workshop Power Conditioning System

**Technology Roadmap**
**for Increased Power Electronic Grid Applications and Devices**

**May 24, 2012**
**NIST Headquarters, Gaithersburg MD**

**Proceedings Prepared By**

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# List of Abbreviations

| | |
|---|---|
| AC | Alternating Current |
| ADEPT | Agile Delivery of Electrical Power Technology |
| AMDR | Air and Missile Defense Radar |
| ARRA | American Recovery and Reinvestment Act of 2009 |
| ARPA-E | Advanced Research Project Agency-Energy |
| BTU | British Thermal Units |
| CPES | Center for Power Electronics Systems |
| DC | Direct Current |
| DOE | Department of Energy |
| DOD | Department of Defense |
| DG | Distributed Generation |
| EPRI | Electric Power Research Institute |
| ESS | Energy Storage Systems |
| FIDVR | Resistance to Fault Induced Delayed Voltage Recovery |
| EIA | Energy Information Agency |
| FY | Fiscal Year |
| GaN | Gallium Nitride |
| GENI | Green Energy Network Integration |
| GW | Giga Watt |
| GWh | Giga Watt-hour |
| HF | High Frequency |
| HM | High Megawatt |
| HMW | High Megawatt Workshop |
| HV | High Voltage |
| HVDC | High Voltage Direct Current |
| IGBT | Insulated Gate Bipolar Transistor |
| IOU | Investor Owned Utilities |
| ISO | Independent System Operator |
| ITC | Investment Tax Credits |
| GEN | Generation |
| JBS | Junction Barrier Schottky |
| JFET | Junction Field-Effect Transistors |
| kHz | kilohertz |
| kV | kilo Volts |
| kVA | kilo Volt Ampere |
| kW | kilo Watt |
| kWh | kilo Watt-hour |
| LCOE | Least Cost of Electricity |
| LVRT | Low Voltage Ride Through |
| m | meter |
| MEMS | micro electromechanical systems |
| MOSFET | Metal-Oxide Semiconductor Field-Effect Transistor |
| MVA | Mega Volt Amperes |

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| | |
|---|---|
| MW | Megawatt |
| MWh | Megawatt hour |
| NIST | National Institute of Standards and Technology |
| O&M | Operating and Maintenance |
| PCS | Power Conditioning System |
| PEM | Proton Exchange Membrane |
| PTC | Production Tax Credits |
| PV | Photovoltaic |
| RPS | Renewable Portfolio Standards |
| R&D | Research and Development |
| Si | Silicon |
| SiC | Silicon Carbide |
| SGTO | Super Gate Turnoff Thyristor |
| SSPS | Solid-State Power Substation |
| TDS | Traction Drive System |
| THD | Total Harmonic Distortion |
| T&D | Transmission and Distribution |
| US | United States |
| VAC | Volts AC |
| VACRMS | Volts AC Root Mean Square |
| WEG | Worldwide Equipment Guide |

# 1. Summary

On May 24, 2012, 32 invited participants convened in a workshop held at NIST (National Institute of Standards and Technology) headquarters in Gaithersburg, Maryland. Three technical sessions, at which 12 presentations were given, were titled:

- Applications and Drivers for Increasing Grid PCS (Power Conditioning Systems)
- Advanced HM (High Megawatt) PCS Technologies and Approaches
- Technology Development Programs

The complete set of presentations can be viewed or downloaded at the NIST High Megawatt Workshop (HMW) site at http://www.nist.gov/pml/high_megawatt/may-2012_workshop.cfm.

The major conclusions that can be drawn from the presentations and discussions at this Workshop are that:

The existing electrical grid needs replacement of aging components, expansion of capacity to accommodate increased population and increased per capita use of electricity, utilization of advanced PCS to improve transmission efficiencies, initiate some control of power flows, and to better cope with the issues resulting from the increased delivery of intermittent and rapidly fluctuating power from solar and wind generators.

The growing availability of high quality SiC material and SiC–based components and devices has enhanced the capabilities of PCS components such as Schottky diodes, JBS (Junction Barrier Schottky) diodes, JFETs (Junction Field-Effect Transistors),~~ and~~ MOSFETs (Metal-Oxide Semiconductor Field-Effect Transistor), and Insulated Gate Bipolar Transistors (IGBT). Many of these devices~~items~~ have capabilities that cannot be achieved with Si-based components. The number, capability, and commercial availability of these products is increasing rapidly at this time and can play a significant role in upgrading the US electrical grid.

This commercial availability of SiC-based components is attributable in large part to the long-term funding of R&D (Research and Development) programs that has been provided by numerous agencies of the Department of Defense (DOD) as well as by other federal agencies including NIST and ARPA-E (Advanced Research Projects Agency-Energy). Much of this R&D has been done by integrated teams that have included private sector companies, national laboratories, and universities.

Additional research and development is needed to improve PCS systems to meet specific DOD operational requirements and ARPA-E goals of ensuring the economic and energy security of the US (United States) and to ensure that the US maintains the technological lead in developing and deploying advanced energy technologies.

# 2. Introduction

**Workshop Structure**

The stated objectives of the Workshop were summarized in the invitation to participants:

"The purpose of this workshop is to gather those with strong interests in achieving higher levels of power electronic penetration in our power grid. Power grids of the future will have to withstand increasing stresses caused by elements such as large-scale energy trading, and a growing share of fluctuating energy sources, such as wind and solar power. The grids therefore must become more flexible and better controlled. State-of-the-art and developing power electronics provide a wide range of solutions. Given this, the intent of the Workshop is to discuss some of the most salient technical, economic, regulatory and political challenges; and to roadmap key solutions."

Three technical sessions, at which 12 presentations were given, were titled;

- Applications and Drivers for Increasing Grid PCS
- Advanced High Megawatt PCS Technologies and Approaches
- Technology Development Programs

The presentations were followed by a Discussion session titled:

- Technology Roadmap to Align Expectations

During the Discussion session, the following issues were addressed:

- Applications' Requirements:
- Stakeholders
- System Performance Issues
- Technical Barriers/Issues

**Background**

The existing US grid has been designed to operate with relatively constant inputs of AC (Alternating Current) power from large electricity generating plants. Power flows are now essentially uncontrolled, following the paths of least resistance through the grid. New issues that challenge the stability and performance of the grid have emerged, including the nearing of end of service life for some of the oldest components, identification of many points of congestion due to overloading of existing lines, and issues associated with intermittent and rapidly fluctuating deliveries of power from solar and wind generators, which have produced stability problems in some instances.

As a result of significant subsidization of "green" power production by solar, wind, and fuel cell technologies including federal and state R&D funding, ITC (Investment Tax Credits), PTC (Production Tax Credits) and RPS (Renewable Portfolio Standards), the amount of electricity generated by these new solar and wind generators has continued to increase. As shown in Table 1, the Reference Case published in the EIA (Energy Information Agency) 2012 Annual Energy Outlook (Tables A18 and A8) predicts further increases in the future.

**Table 1. Prediction of Solar and Wind Power Growth**

| **Electricity Production. Billions of kWh** | **2010** | **2020** | **2035** |
|---|---|---|---|
| Solar (not including off-grid PV (photovoltaics) | 4.48 | 23.87 | 43.96 |
| Wind | 94.95 | 154.40 | 194.23 |
| Total of Solar and Wind | 99.43 | 178.27 | 238.19 |
| Total US Production | 3955 | 4084 | 4572 |
| % Solar and Wind of Total US Production | 2.51 | 3.78 | 5.20 |

These predicted significant increases in solar and wind power production are dependent in part on both continuing federal and state subsidy programs and the future price of natural gas. With large increases in the rate of natural gas production that has been achieved to date from shale formations and further increases anticipated, the price of natural gas, now about $3/million BTU (British Thermal Units), results in natural gas fueled power being cheaper than non-subsidized solar and wind power.

Current issues with grid instability have been experienced at times of peak wind power availability in Europe, the Bonneville Power Administration system and in Texas, all of which have large wind power facilities. The ability to control power flows within the grid will allow transmission of additional net power flows through the grid by avoiding reaching congestion points on specific lines. The SiC to replace Si (Silicon) in many components of PCS is leading to cost effective performance of newly developed devices in many applications. Power flow control tHaving cost-effective technology based on newly available SiC based SiC components and devices is likely to be less costly than expanding the grid with current technology. Both Sstate-of-the-art and developing, power electronics provide a wide range of solutions to current grid issues.

## 3. Brief Summaries of Presentations

This section of the Proceedings presents brief summaries of each of the Technical presentations. The complete set of presentations can be viewed or downloaded at the NIST High Megawatt Workshop site at http://www.nist.gov/pml/high_megawatt/may-2012_workshop.cfm.

### A. Applications and Drivers for Increasing Grid PCS

**Wind PCS Architectures**

Over the last 33 years, the output and size of typical state of the art wind turbines has increased from 30 kW (kilowatt) with 10 m (meter) rotors in 1979 to 3000 kW with 90 m rotors (175 m high structure) in 2003. The recently announced next step will be a 7000 kW machine with a 164 m rotor. Impediments for wide proliferation of wind assets are the cost of wind generation (capital and maintenance), risks associated with variability of wind (intermittency and unpredictability), barriers for transmission (transportability), and compliance with smart grid infrastructure requirements.

Companies that manufacture wind generators need a long-term business case certainty to support sustained investment. Profitability will be attained only if wind powered LCOE (Least Cost of Electricity) without the benefits of ~~-~~PTC and other subsidies is less than the LCOE of power produced with gas turbines fueled with natural gas.

It appears that HVDC (High Voltage Direct Current) ~~appears to~~might be the future technology of choice to transport power from wind power plants over long distances (e.g. from deep water offshore to onshore). However, significant challenges are needed in protection and control of such DC architectures.

Other R&D power conversion activities that have the potential to lead to lower wind power costs are:

- Technology to reduce the cost of crossover from low voltage to medium voltage to HVDC
- Utilization of combinations of technologies (e.g. hydraulic transmissions with synchronous generators coupled to the grid).
- DC turbines combined with DC collection has the potential to offer up to 30% improvement in reducing energy losses. This improvement is obtained through reduction of turbine-side and station-side converters. However, the challenge is in realizing such high power DC/DC converters.

**(Manjrekar)**

**Solar Power Integration**

Solar Power generating systems have the attributes of no fuel or O&M (Operating and Maintenance) expenses. The cost of capital required for large installations is the major expense. It is typically provided by IOU (Investor Owned Utilities) that put in their rate base, or by public power agencies through bond financing.

The major trends currently in grid modification and upgrading are that new major transmission installations are DC and that Back-to-Back DC links that are inserted in major AC ties. The increasing amounts of widely dispersed small-scale DG (Distributed Generation), which is primarily solar, offers the potential for Reactive Power control and Ancillary Services via PCS, improved system stability, and FIDVR (Resistance to Fault Induced Delayed Voltage Recovery). Advanced communications and control of inverters will enable PV to virtually behave like conventional generation

Given the availability of high power PCS at the transmission level, DG systems can have the same characteristics; DG can/will be centrally controlled, but with highly autonomous ~~powers~~functions, and distributed PCS can/will replace capacitors, regulators, etc. This combination can lead to a truly coordinated, inherently stable, self-healing grid.
**(Reedy)**

**Fuel Cell Power Integration**

The challenge facing fuel cell power plants over the last thirty years has been that their delivered capital cost has been too high to compete with grid-delivered electricity. However, there have been a large number of sites where superior environmental performance and very high reliability have provided enough value to the owner to justify the relatively high capital cost. In many cases, subsidies from federal and state governments have reduced the owner's cost to an acceptable level.

Direct FuelCell (DFC)® power plants (300 kW, 1400kW and 2800 kW) manufactured by FuelCell Energy that utilize molten carbonate technology are generating ultra-clean, efficient and reliable power at more than 50 distributed power locations worldwide. Over 180 megawatts of power generation capacity has been installed or is in backlog. Multi-MW sites (4x2800kW) rated at 11.2 MW at Daegu, South Korea, and a 10.4 MW facility at Yulchon, South Korea with a 22.9kV express feeder connection to the sub-station are in operation

From 2003 to 2010, Fuel Cell Energy achieved 70% $/kW cost reduction in their fuel cell power plants through value engineering, ~~power~~ power-up-rating~~rate~~, and economy of scale.

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FuelCell Energy is actively implementing micro-grid mode at several sites including Central Connecticut State University (Gensets and 1.4 MW fuel cell ), San Jose Water Treatment Plant (Gensets and1.4 MW fuel cell) Santa Rita County Jail (DOE Smart Grid Demonstration {Facility Static Switch Disconnect, 1 MW early generation Fuel Cell, Gensets,1 MW solar, 2 MW energy storage})

Distribution system limitations have been encountered including the need for Express Feeders for systems larger than 1.5/3.0 MW, voltage regulation, and protection scheme limitations at sub-station minimum loads. Smart grid technologies may reduce technical, jurisdictional, and statutory constraints. In Germany, LVRT (Low Voltage Ride Through) is required for fuel cells connected to the Medium Voltage Network (i.e. Distribution Systems).

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**(Bernsten)**

UTC Power manufactures phosphoric acid fuel cells for stationary power markets and Proton Exchange Membrane (PEM) fuel cells for transportation markets. Their PC50 product for the stationary power market utilizes four Cell Stack Assemblies in series to produce 400 kW at greater than 850V at base load. Forty-two of these units have entered service since 2010. Previous 200 kW products were placed in service in more than 250 installations. Examples of PC50 product installations are Price Chopper (New York), St. Helena Hospital (California), The Octagon (New York), Coca-Cola Enterprises (New York), Samsung/GS Power (South Korea), and the World Trade Center (Freedom Tower, New York).

These units contain 470 kVA (kiloVolt Amperes) inverters which are directly connected to the grid with no isolation transformer. The PCS is ~97% efficient. Fifty percent production cost reduction has been achieved since production of the first seven units in 2011. Another 30% cost reduction is needed to reach their cost goals

Their PC40 product for transportation markets produces 120 kW from PEM stacks. Eighteen quiet, zero-emission fuel cell buses are currently in service in the United States. The PCS system utilizes a modular inductor, dc-dc converter and inverter modules. A 25% cost reduction was achieved relative to the first seven units produced in 2010. An up-rated 150 kW PC58 product for these markets is now in the conceptual design phase. The goal is a 60% cost reduction resulting from the increased power rating and improved integration with external systems.

**(Singh)**

**Grid Storage Integration**

Grid-tied energy storage mediums are predominately DC in nature.  To effectively utilize the energy storage capacity on the present electric utility grid, the energy must be converted to a standard AC level and regulated through a converter.  Converters used for this purpose must achieve bi-directional conversion from AC to DC and DC to AC, AC grid to DC storage isolation and protection, interconnection and control of multiple DC sources, and regulated, stable and controllable power flow.

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Basic inverter operation includes sinusoidal pulse width modulation and phase locked to grid, reference signal provided to compare with triangle waveform, gates are triggered as output of controller modulation is provided to control power, and output is filtered to provide limited harmonics/switching noise.

Basic AC/DC power conversion topologies include both Single Stage Converters and Multi-Stage Converters. Single Stage Converters are limited to DC voltages > 1.5X VACRMS (Volts AC Root Mean Square) and designed to achieve maximum efficiency. Multi-Stage Converters are characterized by maximum DC voltage range, increased losses, and increased hardware cost. Advanced power conversion topologies include multi-port/multi-stage converter, Z-inverter, and multi-level inverters.

The key conclusions from this presentation are:

- Power conversion is an integral part of ESS (Energy Storage Systems)
- Limit conversion stages are used to maximize efficiency and minimize complexity
- Integrate systems as soon as practicable to avoid grid interaction and maximize efficiency
- Modularized systems offer unique advantages in redundancy and expandability
- Advanced and hybrid topologies may offer the best solution for specific ESS challenges.

**(Clark)**

## B. Advanced High Megawatt PCS Technologies and Approaches

**PCS Connected Microgrids**:

Pareto Energy offers a packaged unit to safely connect microgrids ~~grids~~ to utility grids by means of a parallel non-synchronous interconnection. The package is similar in size to a shipping container, requiring a pad with a length of about 50 feet. The packaged unit is designed for drop-in installation with no on-site fabrication.

The contents of the package includes active rectifiers, packaged output inverters, switchgear and a 4 MVA transformer. Functionally, it has been designed to eliminate the potential of voltage, frequency, and phase-angle mismatching between the facilities and the utility grid and preclude any potential detrimental effects on the utility power delivery system.
**(Flank)**

**Advanced HMW Converters**

Electrical grids come in many sizes. Among the largest are the regional US power grids. Microgrids exist in neighborhoods and commercial sites. Homes can be considered as nano-grids, while the combination of an auto and recharger can represent a pico-grid. Most electricity is consumed by electronic loads, which are constant-power loads. In the future, more electricity may be supplied by DC electronic sources such as renewables, batteries, and pumped storage, as ~~if~~ these systems increase in size.

The CPES (Center for Power Electronics Systems) at Virginia Tech has set up a home DC nano-grid experiment. It has a bus architecture with two voltages, wireless communication, bidirectional power conversion, separation of dynamics, integrated protection, load management, DG management, data acquisition, communication, and islanded operation.

In addition, CPES is experimenting with a 10 kW, 20 kHz Prototype single-phase nano-Energy Control Center with bi-directional topology, bi-directional control system, bi-directional current limit, bi-directional EMI compatibility, and low dc leakage current, all with low cost and high density.

Many system configurations are possible for multi-level converters for high-voltage applications including Neutral Point Clamped, Diode Clamped, Active Clamped, Flying Capacitor, Cascaded, Cascaded H-Bridge, ~~Asymetric~~Asymmetric Cascaded H-Bridge, and Modular Multilevel

Research is recommended in the areas of Network Architectures and Control, High-Power and High Power-Density Converters, and Safety and Reliability to replace electric energy "railways" with "highways". Education is recommended to instigate an innovative intellectual "Ecosystem" in the areas of Network Architectures, Energy Transfer Protocols and Markets, High-Power and High Power-Density Converters, and Safety and Reliability.
**(Boroyevich)**

**SiC Power Devices/Materials:**

The commercial availability of high quality (low defect concentration) SiC in steadily increasing size wafers at steadily lower prices has allowed the commercial development of multiple high performance devices which have markedly improved performance relative to Si-based devices. The significant properties of SiC relative to PCS are:

- 10X Breakdown Field of Si
  - Allows lower specific on-resistance and faster switching for the same breakdown voltage
- 3X Thermal Conductivity of Si
  - Allows higher current densities
- 3X Bandgap of Si
  - Allows higher temperature operation

Currently available SiC-based products from Cree Inc. include 1-20A 600V Z-Rec SiC JBS diodes, 4-20A 650V Z-Rec SiC JBS diodes, 2-40A Z-Rec 1200V SiC JBS diodes, 5-50A 1200V SiC JBS diodes, 10 and 25A 1700V Z-Rec SiC JBS diodes, and new

1200V/50A & 1700V/50A SiC JBS diodes and MOSFETs which are scheduled to be released in the ~~fall~~ Fall of 2012.

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Cree Inc. shipped 113 GVA (Giga Volt Amps) of SiC related products in 2011. Since 2005, cost reductions of over 5x have been achieved as a result of higher quality SiC material, larger production volumes, and an increase in SiC wafer size from 3 inch to 100 mm. The Field Failure Rate since January 2004 has been 10 times lower than the typical silicon

Since the mid 2000's several high voltage (>10 kV) SiC devices have been developed and demonstrated in power converters; for example 10 kV SiC MOSFETs have been demonstrated in Megawatt scale power converters switching at >20 kHz. Highlights of the SiC IGBT (Insulated Gate Bipolar Transistor) recently ~~development~~ developed under the ARPA-E ADEPT ~~-~~(Agile Delivery of Electrical Power Technology) Program include:

- Development of 15 kV SiC IGBT – World's highest voltage semiconductor switch
  - Over 2x higher than 6.5 kV SiC IGBT
- SiC IGBTs are capable of switching over 20x faster than Si IGBTs
- Higher voltage and switching speed of SiC IGBTs enables a 3x to 5x reduction in the size and weight of a Solid State Transformer
- SiC IGBTs result in a 3x to 4x reduction in losses for that Solid State Transformer

**(Grider)**

**<u>Silicon Carbide Device Update</u>**

The advantages of SiC relative to other power semiconductor materials include

- Most mature "wide bandgap" power semiconductor material
- Electrical breakdown strength ~ ~~10X~~ 10x higher than Si
- Commercial substrates available since 1991 –
  - now at 100 mm diameter, 150 mm diameter soon
- Defects up to 1,000 times less than GaN (Gallium Nitride)
- Thermal conductivity ~ ~~3X~~ 3x greater than Si or GaN

Important applications for SiC-based devices are:

- Low voltage-PFC/Power supplies
- Medium voltage-PV inverters, motor controllers, hybrid automotive
- High Power – ships and vessels, smart power grid, windmills, rail transport

SemiSouth Laboratories offers 1200 V – 1700 V Trench "normally – off" JFETs, 650 1200V-1700V Trench "normally – on" JFETs, and 1200 V Schottky diodes. SiC Trench JFET offers lower cost, 3-10 ~~X~~ x smaller die size and up to 50% fewer manufacturing steps. Performance attributes include 5-~~10X~~ 10x lower switching energies, normally-on or -off, which enables both high-frequency and high-efficiency operation.

Using SemiSouth Laboratories SiC JFET, Future Power Electronics Technology developed an all-SiC-device-based three-phase inverter with a 500 cc volume, verified to achieve an output power density of 30kWh/l, which is believed to be the highest achieved to date. The power modules in the device operate at up to 200°C. At 15 kW output, the conversion efficiency of this 500 cc device was 99%.
**(Sheridan)**

## C. Technology Development Programs

### Army Programs

Power loads continue to rise on all military platforms. Mission capability on both current and future platforms is driven by effective use of electric power. SiC-based converters provide greater power density and finer control than Si-based converters. However, their maturity-/reliability and cost is still considered a risk factor by Army Program Managers. There is a major focus on increased efficiency and temperature for size reduction and fuel economy.

Soldier requirements are for a 72 hour mission using high energy batteries, hybrid power sources, and photovoltaic technologies in sizes of microwatts to 10s of watts. Requirements for mobile systems include Silent Power using Fuel Cell auxiliary power systems, Reforming, and Power MEMS (micro electromechanical systems) technologies in air or ground domains in sizes 100s of watts to 100s of kW. Platform technologies on the ground require high power switching and conditioning, intelligent power management, and integrated thermal management in sizes up to 1000s of MW.

**Comment [ARH1]:** Not defined.

The Army anticipates multiple benefits accruing from the use of SiC power electronics including reduced SWAP (system Size Weight ~~and~~ And Power), reduced cooling requirements, increased efficiency at high voltage, and higher operating temperatures. Overall, these will be easier to integrate onto military ground vehicles than silicon based systems and provide significant improvements in mobility performance and fuel economy. Requiring SiC high-frequency operation (in the future at high-temperature) will push the limits of the devices as well as the packaging technology and passive components.

Pulse Power electronic survivability architecture is being developed to support hybrid armor, external power distribution (uncooled), and a store of local high power energy without the engine operating. The challenges include the needs for high temperature, high frequency, high current, low loss switching, high temperature advanced magnetics, high temperature/density storage and conversion capacitors, high voltage “power brick” battery, ultra-fast high-voltage GW switches and cooling through conduction only.

The SiC ManTech program (FY(Fiscal Year) 2004-2009; under ARRA (American Recovery and Reinvestment Act of 2009) since FY2011) has focused on development of SiC power MOSFET and diode development to replace Si power electronics. Future

**Comment [ARH2]:** Not defined

plans for this program include development of GEN(Generation)-1 (ManTech) 1.2 kV / 80 A SiC MOSFETs and Schottky diodes, GEN-1 (ARA) 1.2 kV / > 100 A SiC MOSFETs and GEN-2 1.2 kV / >200 A SiC MOSFETs (WEG (Worldwide Equipment Guide)>100°C).

Future plans for SiC power switch development for continuous power applications include a SiC TDS (Traction Drive Systems) module operating at 80°C and 100°C WEG ~~(Worldwide Equipment Guide)~~, with 70% greater efficiency than Si TDS module and at 40% replacement, and to mature MOSFET to 300 A @ > 100°C WEG.

**Comment [ARH3]:** Not defined

Planned developments focused on Pulse Power applications include Si SGTO (Super Gate Turnoff Thyristor) die pulse switch operating at ~~10X~~ 10x power density of Si whole-wafer switch, SiC SGTO die operating at 2 ~~X~~ x greater power density than Si SGTO die and programs to mature SiC switch power density by another 2-~~3X~~ 3x at increased efficiency.

This component work can reduce power system size by up to ~~2X~~ 2x for continuous and ~~4X~~ 4x for pulse power applications with efficiencies at >~~2X~~ 2x compared to Si-based systems.
**(Scozzie)**

## Navy Programs

The SSPS (Solid-State Power Substation) is part of the DARPA High Power Electronics (HPE) program. The objective is to develop compact, light-weight power converters and transformers for the US Navy~~,~~ that are enabled through high voltage switches. A single-phase SSPS has undergone testing at the Navy test lab with the following results:

- Demonstrated at 1 MVA, 13.8 kV/265 V
- Based on 10 kV, 120 A, 20 kHz SiC MOSFET/JBS-diode Modules
- Efficiency at full load > 97%
- 1/3~~rd~~ weight of conventional transformer
- Clean 20 kHz waveforms
- Balanced sharing of voltages/~~-~~currents
- AC input current, ~~/~~ output voltage THD (Total Harmonic Distortion) < 5%
- Cooling of HF transformers and busbar/connections is challenging

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A 1 MW, 4160Vac – 1000Vdc supply prototype is now under assembly for AMDR (Air and Missile Defense Radar) ~~radar~~ service and is scheduled for TRL6 (Technical Readiness Level 6) testing in the fourth quarter of 2012. It is also based on the 10 kV, 120 A, 20 kHz SiC MOSFET/JBS-diode Modules and has 1/3~~rd~~ the volume and 1/10~~th~~ the weight of the existing supply.

**Comment [ARH4]:** Not defined

Potential industrial applications for this type of unit include

- Renewables

    - Enable power conversion and grid interface at higher voltage to reduce complexity and cost
- Rail
    - More efficient locomotive drives - reduce switching/diode recovery losses
    - Compact transformers/electronics for catenary interface
- T&D
    - Reduce number of series devices needed to handle high voltage~~.~~
    - HVDC/ FACTS (Flexible AC Transmission) converters with lower component count/complexity
    - Compact solid-state distribution transformers
    - (smaller footprint, added functionality, oil-free)

Challenges for high voltage SiC material in this application include:

- Cost – need market volume and higher yields
- Reliability - need validation from early adopters
- Limited current ratings for present devices/ modules
    - T&D (Transmission and Distribution), Drives, Wind applications will require higher ratings
    - Need large-area chips with good yields
- Development of supporting HV (High Voltage) components – passives, gate drives, packaging, insulation
- For HV applications, they need to be cost-competitive compared with multilevel converters with LV (Low Voltage) silicon

**(Beermann-Curtin~~s~~)**

**ARPA Programs**

The major ARPA-E missions are to enhance the economic and energy security of the US and to ensure that the US maintains the technological lead in developing and deploying advanced energy technologies. The strategies are to find and fund high-risk, high-impact projects, invest in the best ideas and teams, tolerate and manage high technical risk; accelerate translation from science to markets, and fund both proof of concept and prototyping.

ARPA-E has a number of technology development programs under way including GENI (Green Energy Network Integration) to make the existing grid stronger and more reliable, have the flexibility to dispatch power in real time, and to enable ~~10X~~ 10x more renewable energy to flow through the grid to power customers. Both hardware and software development are supported.

GENI architectures for the grid are focused on routing electrical power and mobilizing large numbers (100k) of small assets. Topology Control Algorithms are being developed to optimize the performance of individual transmission lines. Projects utilizing multi-party teams are involved in the development of HV grid-scale transistors, Solid-State

Transformers (SST), power routers to augment existing transformers, utility-scale inverters, distributed inverters, and micro-inverters.

Specific project examples from ARPA-e GENI, ADEPT, and Solar-ADEPT programs include:

- Development by Cree of a 15 kV/20 A SiC p-IGBT -- the world's highest voltage semiconductor switch
- Scalable real-time decentralized Volt/VAR (Volt Ampere Reactive) control. Key innovations include distributed control through local sensing, computation, and communication, yet jointly optimize certain global objectives and characterization of AC-OPF sub-problems that are polynomial-time solvable
- Open ADR (Automatic Demand Response), low-cost, internet-protocol based telemetry solutions, and intelligent forecasting and optimization techniques to provide "personalized" dynamic price signals to millions of customers in timeframes suitable for providing ancillary services to the grid
- Utility scale 1 MW Photovoltaic Inverter to cost an estimated $0.2/W (in China $0.17/W)

**(Gradzki)**

## 4. Discussion - Technology Roadmap to Align Expectations

**Application Requirements**

Different organizations have different but very specific requirements related to the specific operations that they are planning to carry out. For example the Army and Navy often have very strict performance goals for specific equipment items. These items are subject to weight, space, fuel consumption, electrical efficiency and other constraints not required in conventional, non-defense applications. Electrical efficiency is very important when producing electricity either on-board or on-site fueled from an off-site location. These different constraints establish different values that the customer is willing to pay for the component, device or system. There are limited markets for high-priced, low value production items. If the market doesn't expand it is difficult to reduce the price of an item.

**Stakeholders**

The 32 Workshop participants represented a very broad group of interests. The most heavily represented group was the equipment vendors (13), followed by federal agencies (7) (including ARPA-E (3) DOE (2), ORNL (Oak Ridge National Laboratory) (1) and NIST (1), DOD (3)), universities (4), state agencies (2) consultants (2), and ISO (Independent System Operator) (1). At this workshop~~Unfortunately~~, we were not able to benefit from the participation of power producers, either IPP or utility, that have to deliver their product to market via T&D systems. Several organizations including ARPA-E are funding R&D to increase the efficiency of and reduce the cost of transmission.

**System Performance Issues**

One of the overriding issues at both the state and federal levels is the avoidance of wide-area blackouts, which often result in actions taken automatically to protect the grid from instability. It has been suggested that relaxing some of the frequency regulation standards by a small amount, could result in a major reduction in the probability of an area-wide black-out due to automatic control actions.

One of the major difficulties in reducing the cost of PCS ~~package~~ products is the fact that the core inverter technology represents only about 30% of the total cost of that product~~package~~. Reducing only cost of the core inverter technology, without major reductions in the other components in the product~~package~~ can only result in a small reduction in overall cost.

The ARPA-E cost goal for PV inverters is 10¢/W. Is that low enough for PV solar and other applications? Can it be achieved?

**Technical Barriers/Issues**

In order to gain the confidence of potential customers, very extensive field testing of components, devices, and systems is required to demonstrate ~~those items system~~that they will perform as specified under the conditions specified, for the lifetime specified with the reliability specified. Both prototypes and full-scale items must be tested extensively to meet these requirements

A number of Army, Navy and ARPA-E test programs that are briefly noted below were described at the Workshop.

- The Navy is successfully testing ~~of~~ a single-phase SSPS, with 1/3~~rd~~ the weight of conventional transformer at 1 MVA, 13.8 kV/265 V with > 97% efficiency at full load. Further testing of a 1 MW, 4160Vac – 1000Vdc supply prototype with 1/3~~rd~~ the volume and 1/10~~th~~ the weight of the existing supply is scheduled for TRL6 (Technical Readiness Level 6) testing in fourth quarter of 2012.

- The Army is developing a variety of components that have evolved from earlier lower power components, including 1.2 kV / 80 A SiC MOSFETs and Schottky diodes, 1.2 kV / >100 A SiC MOSFETs , 1.2 kV / >200 A SiC MOSFETs (WEG >100°C).

- Southern Company is testing Power Flow Controllers which augment existing transformers developed by a team consisting of Waukesha, Varentec, Georgia Tech. and EPRI (Electric Power Research Institute) with ARPA-E funding. 13 kV/1MW units are being evaluated in a tie-line field demo and ~~in~~ a 13 kV, 5 bus test bed is in operation to show routing.

- A multistage PV inverter that utilizes high-voltage switches and a high-frequency transformer has been developed by Ideal Power Converters. It has 1/10 the weight, 1/3 lower losses and 1/2 the manufacturing costs of comparable units in service today**.**

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# 4. Conclusions

The major conclusions that can be drawn from the presentations and discussions at this Workshop are that:

The existing electrical grid needs replacement of aging components, expansion of capacity to accommodate increased population and increased per capita use of electricity, utilization of advanced PCS to improve transmission efficiencies, initiation of some control of power flows, and development of capability to better cope with the issues resulting from the delivery of increased penetration levels~~delivery~~ of intermittent and rapidly fluctuating power from solar and wind generators.

The growing availability of high quality SiC material and SiC–based components and devices has enhanced the capabilities of PCS components such as Schottky diodes, JBS (Junction Barrier Schottky) diodes, JFETs (Junction Field-Effect Transistors), ~~and~~ MOSFETs (Metal-Oxide Semiconductor Field-Effect Transistor), and IGBTs. Many of these items have capabilities that cannot be achieved with Si-based components. The number, capability, and commercial availability of these products is increasing rapidly at this time and can play a significant role in upgrading the US electrical grid.

This commercial availability of SiC-based components is attributable in large part to the long-term funding of R&D (Research and Development) programs that has been provided by numerous agencies of the Department of Defense (DOD) as well as by other federal agencies including NIST and ARPA-E (Advanced Research Projects Agency-Energy). Much of this R&D has been done by integrated teams that have included private sector companies, national laboratories, and universities.

Additional research and development is needed to improve PCS systems to meet specific DOD operational requirements and ARPA-E goals of ensuring the economic and energy security of the US (United States) and to ensure that the US maintains the technological lead in developing and deploying advanced energy technologies.

# 6. Appendices

## A. Final Workshop Agenda

**High Megawatt Power Conditioning System Workshop**

**Technology Roadmap**
**for Increased Power Electronic Grid Applications and Devices**

**NIST**

**Gaithersburg Maryland**

**8:30 am to 5 pm, May 24, 2012**

### Workshop Objectives

The purpose of this workshop is to gather those with strong interests in achieving higher levels of power electronic penetration in our power grid. Power grids of the future will have to withstand increasing stresses caused by elements such as large-scale energy trading, and a growing share of fluctuating energy sources, such as wind and solar power. The grids therefore must become more flexible and better controlled. State-of-the-art, and developing, power electronics provide a wide range of solutions. Given this, the intent of the Workshop is to discuss some of the most salient technical, economic, regulatory and political challenges; and to roadmap key solutions.

### Agenda

**8:00am Breakfast**

8:30am Introductions and Objectives Al Hefner/Leo Casey/Ron Wolk

**8:45am Applications and Drivers for Increasing Grid PCS**

| | | |
|---|---|---|
| Wind PCS Architectures: | Madhav Manjrekar | (Vestas) |
| Solar Grid Integration: | Bob Reedy | (Florida Solar Energy Center) |
| Grid Storage Integration: | Kyle Clark | (Dynapower Company) |
| Fuel Cell Integration: | George Berntsen | (FuelCell Energy) |
| | TJ Singh | (UTC Power) |

**10:15am Break**

**10:35am Advanced HMW PCS Technologies and Approaches**

| | | |
|---|---|---|
| PCS Connected Microgrids: | Shalom Flank | (Pareto Energy) |
| Advanced HMW converters: | Dushan Boroyevich | (Virginia Tech) |

| | | |
|---|---|---|
| SiC Power Devices/Materials: | Dave Grider | (Cree Inc.) |
| SiC Power Devices | David Sheridan | (SemiSouth) |

**12:00noon Lunch**

**1:00pm Technology Development Programs**

| | | |
|---|---|---|
| Army programs: | Skip Scozzie | (Army Research) |
| Navy programs: | Sharon Beermann-Curtin | (Office of Naval Research) |
| ARPA-e programs: | Pawel Gradzki | (Booz Allen Hamilton) |

**2:00pm Technology Roadmap to Align Expectations**

| | | |
|---|---|---|
| Discussion Leader: | Leo Casey | (Satcon) |

Applications Requirements:

Control of voltage, power-factor and faults through solid-state devices. Integration and control of renewables and storage. Seamless isolation from grid outages and disturbances through microgrids. Ability to relieve congestion. Achieve improved demand and supply response.

Stakeholders

Power producers, ISOs, grid operators, utilities, power electronic equipment manufacturers, energy and power generation/storage manufacturers. (related stakeholders also include regulators, safety/standards bodies, rate payers, investors)

System Performance Issues

a. Cost, efficiency, reliability, overload, fault behavior
b. Advantages and possibilities

Technical barriers/issues

a. Controls, communications, anti-islanding, lvrt, optimization (device, site, system,… )
b. C&P

Hardware Issues –

a. What are the gaps in terms of devices, systems, integration,

Technology Demonstration Issues

a. Technologies, scale, number

**5:00pm Adjourn**

## B. List of Workshop Attendees

| Name | Affiliation | Email Address |
|---|---|---|
| Beermann-Curtin, Sharon | Office of Naval Research | Sharon.Beermanncurti@Navy.Mil |
| Berntsen, George | FuelCell Energy, Inc | berntsen@fce.com |
| Biondo, Sam | Samuel J. Biondo, ScD, LLC | sjbiondo@verizon.net |
| Boroyevich, Dushan | Virginia Tech - CPES | dushan@vt.edu |
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| Flank, Shalom | Pareto Energy | sflank@paretoenergy.com |
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| Grider, Dave | Cree, Inc. | david_grider@cree.com |
| Hefner, Allen | NIST | allen.hefner@nist.gov |
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| Lukas, Michael | FuelCell Energy, Inc. | mlukas@fce.com |
| Manjrekar, Madhav | Vestas Technology R&D | mamnj@vestas.com |
| Martinez, Luis Arnedo | United Technologies Research Center | arnedol@utrc.utc.com |
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| Rahman, MD Ziaur | Booz Allen Hamilton | Ziaur.rahman@hq.doe.gov |
| Reedy, Robert | Florida Solar Energy Center of UCF | reedy@fsec.ucf.edu |
| Schauder, Colin | Booz Allen Hamilton / ARPA-E | Colin.schauder@hq.doe.gov |
| Schoder, Karl | Center for Advanced Power Systems, Florida State University | schoder@caps.fsu.edu |
| Scozzie, Skip | Army Research Laboratory | charles.j.scozzie.civ@mail.mil |
| Sheridan, David | Semisouth Laboratories Inc. | david.sheridan@semisouth.com |
| Singh, Tejinder | UTC Power | Tejinder.singh2@utcpower.com |
| Soberoff, Mike | Department of Energy, Office of Electricity Delivery and Energy Reliability | mike.soboroff@hq.doe.gov |
| Tang, Le | ABB | Le.tang@us.abb.com |
| Torrey, David A. | Ioxus, Inc. | DavidTorrey@AdvancedEnergy Conversion.com |
| Wang, Jin | Ohio State University | wang@ece.osu.edu |
| Wolk, Ron | Wolk Integrated Technical Services | ronwolk@aol.com |

# C. List of Workshop Presentations

**Beermann-Curtin**
*Next Generation Technologies for Today's Warfighter*
**Sharon Beermann-Curtin –Office of Naval Research**

**Berntsen**
*Fuel Cell Applications for Power Electronics*
**George Berntsen, Fuel Cell Energy**

**Boroyevich**
*Advanced High-Megawatt Converters for New Grid Architectures*
**Dushan Boroyevich, Center for Power Electronic Systems, Virginia Tech**

**Flank**
*PCS Connected Microgrids*
**Shalom Flank, Pareto Technologies, Inc.**

**Gradzki**
*ARPA-E Stimulating Energy Innovation*
**Rajeev Ram, Program Director, ARPA-E and Pawel Gradzki, Booz Allen Hamilton**

**Grider**
*Advanced SiC Power Technology for High Megawatt Power Conditioning*
**David Grider, Anant Agarwal, Sei-Hyung Ryu, Lin Cheng, Craig Capell, Charlotte Jonas, Al Burk, Michael O'Loughlin, Mrinal Das, and John Palmour; Cree, Inc.**

**Manjrekar**
*Wind – challenges, opportunities, and PCS*
**Madhav D. Manjrekar, Vestas**

**Reedy**
*Driven by the Sun --"Powerful" Thoughts on PCS Development*
**Bob Reedy, Florida Solar Energy Center**

**Scozzie**
*Status of SiC Power Devices for Compact High-Efficiency High-Temperature Power Circuits*
**C. J. Scozzie, U. S. Army Research Laboratory**

**Sheridan**
*Silicon Carbide Device Update*
**David Sheridan, Semi South Laboratories**

**Singh**
*Fuel Cell Power Electronics – Status & Challenges*
**Tejinder Singh, UTC Power**

# Madhav Manjrekar


# Wind – challenges, opportunities, and PCS

Dr. Madhav D. Manjrekar
Global Research & Innovation,
Vestas

Vestas

Industry Perspective

Challenges & Opportunities

PCS in Wind

…if I had more time, I would have written a shorter letter…Goethe

# **Vestas**:
# The largest wind turbine manufacturer in the world

## TOP 10 GLOBAL WIND MANUFACTURERS 2005, 2010 (RANK ORDER BY PRODUCTION)

**+25% per year**

| 2005 Company | Country | Production (GW) | 2010 Company | Country | Production (GW) |
|---|---|---|---|---|---|
| 1. Vestas | Denmark | 3.2 | 1. Vestas | Denmark | 6.3 |
| 2. Enercon | Germany | 2.7 | 2. GE Wind | US | 6.0 |
| 3. Gamesa | Spain | 1.9 | 3. Sinovel | China | 5.3 |
| 4. GE Wind | US | 1.3 | 4. Gamesa | Spain | 4.4 |
| 5. Siemens | Denmark | 1.1 | 5. Goldwind | China | 3.6 |
| 6. Suzlon | India | 0.9 | 6. Suzlon | India | 3.5 |
| 7. Repower | Germany | 0.9 | 7. Enercon | Germany | 3.4 |
| 8. Goldwind | China | 0.7 | 8. Dongfang | China | 3.0 |
| 9. Nordex | Germany | 0.5 | 9. Repower | Germany | 2.9 |
| 10. Ecotecnica | Spain | 0.3 | 10. Nordex | Germany | 2.4 |

Europe US China Other Asia

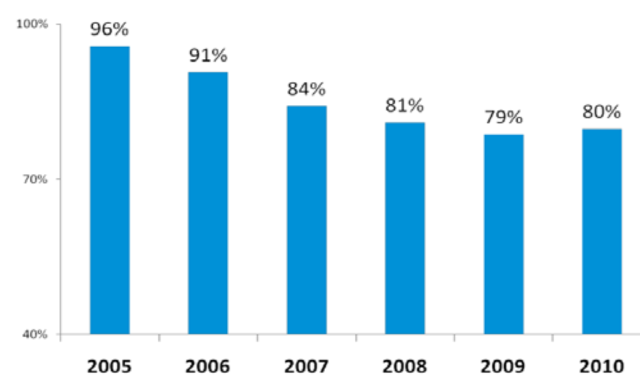
Source: Bloomberg New Energy Finance

### Vestas in Top 10 Markets
Ranking

| Market | MW | No. 1 | No. 2 | No. 3 |
|---|---|---|---|---|
| **China** | 18,928 | Sinovel | Goldwind | Dongfang |
| **USA** | 5,115 | GE Wind | **Vestas** | Siemens |
| **India** | 2,139 | Suzlon Group | Enercon-India | **Vestas** |
| **Germany** | 1,551 | Enercon | **Vestas** | Suzlon Group |
| **UK** | 1,522 | Siemens | **Vestas** | Gamesa |
| **Spain** | 1,516 | Gamesa | **Vestas** | GE Wind |
| **France** | 1,186 | Enercon | Suzlon Group | **Vestas** |
| **Italy** | 948 | Gamesa | **Vestas** | Suzlon Group |
| **Canada** | 690 | Siemens | GE Wind | Enercon |
| **Sweden** | 604 | **Vestas** | Enercon | Siemens |

Source: BTM Consult – part of Navigant Consulting – March 2011

### Market share of top 10 suppliers
Per cent



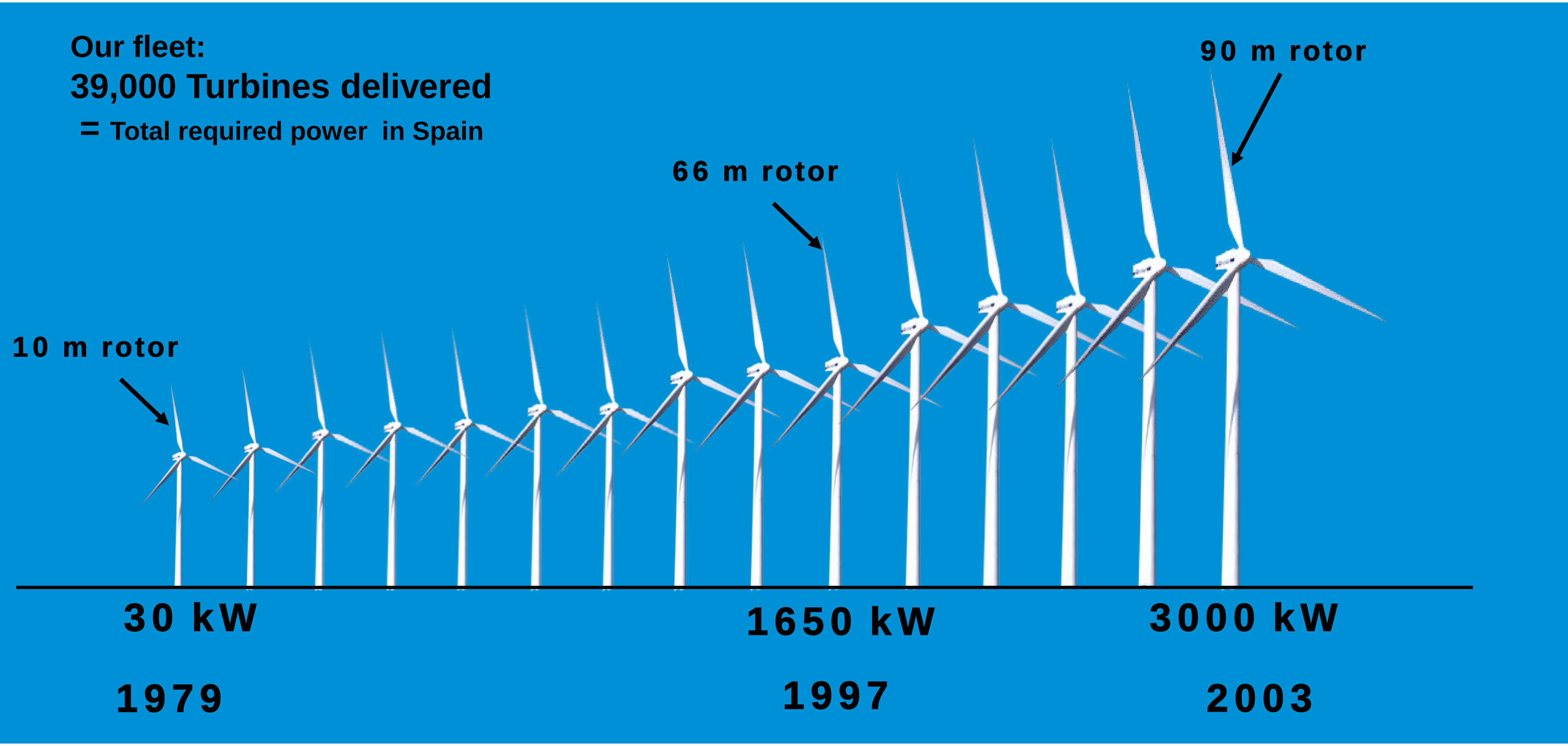

Source: BTM Consult – part of Navigant Consulting – March 2011

On the way up…

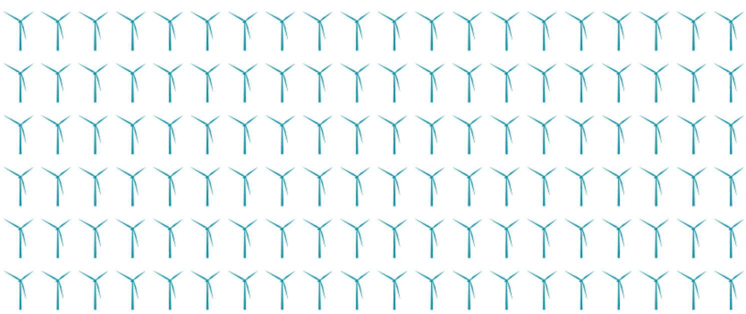
bigger was better…

On the way *not* up…

# Over the last 25 years, the output of a single Vestas turbine increased 100x – total annual energy increased 330x



# Today one turbine produces 3000 kW

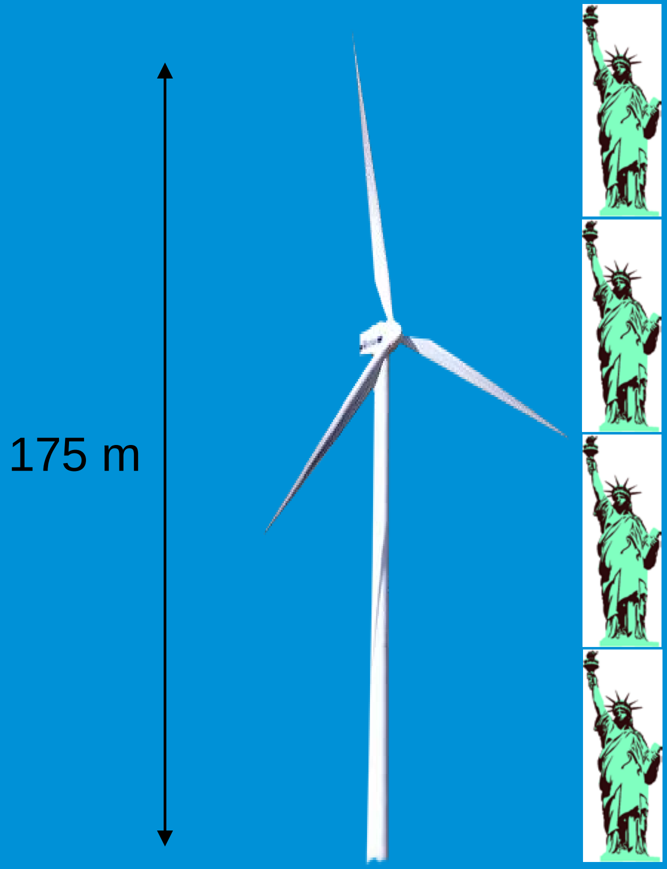


**25 years ago, this was 3000 kW**

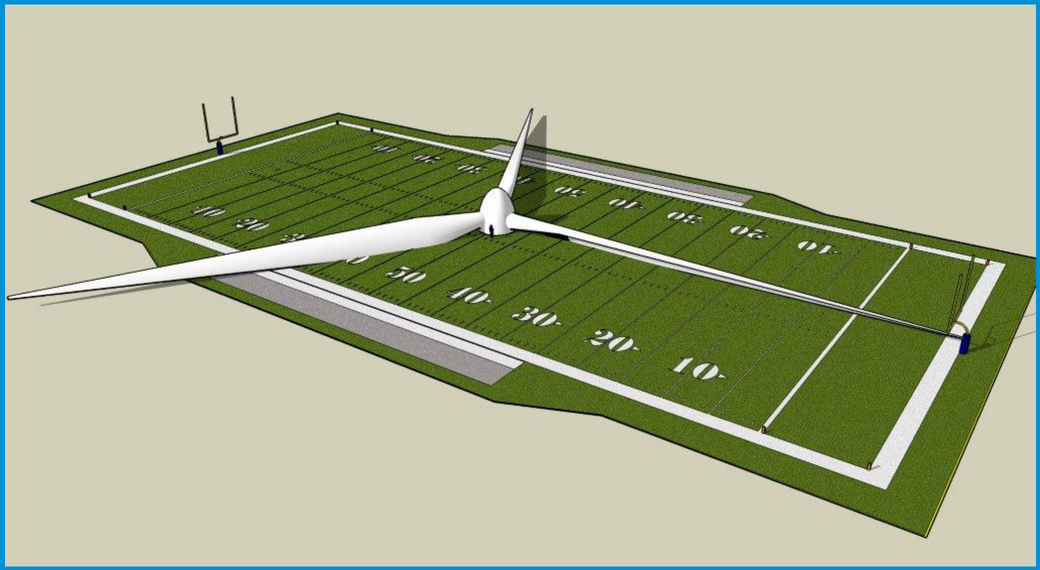
=

**Today, 1 turbine is enough**

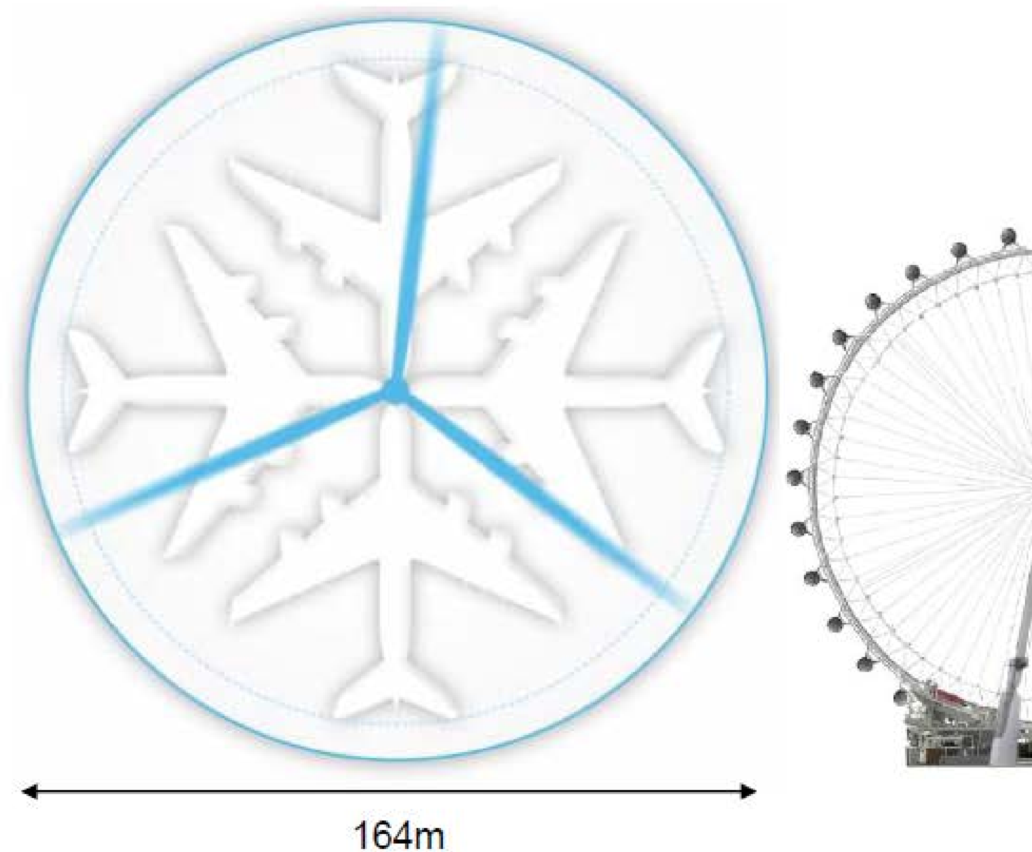
# One V112 = 3.8 Statues of Liberty…




…and its rotor alone won't fit in a football field



# How big will be the recently announced V164?




V-164 7MW – rotor diameter: 164m
Airbus A380 – wingspan: 80 m, length: 73m
London Eye – diameter : 135m.

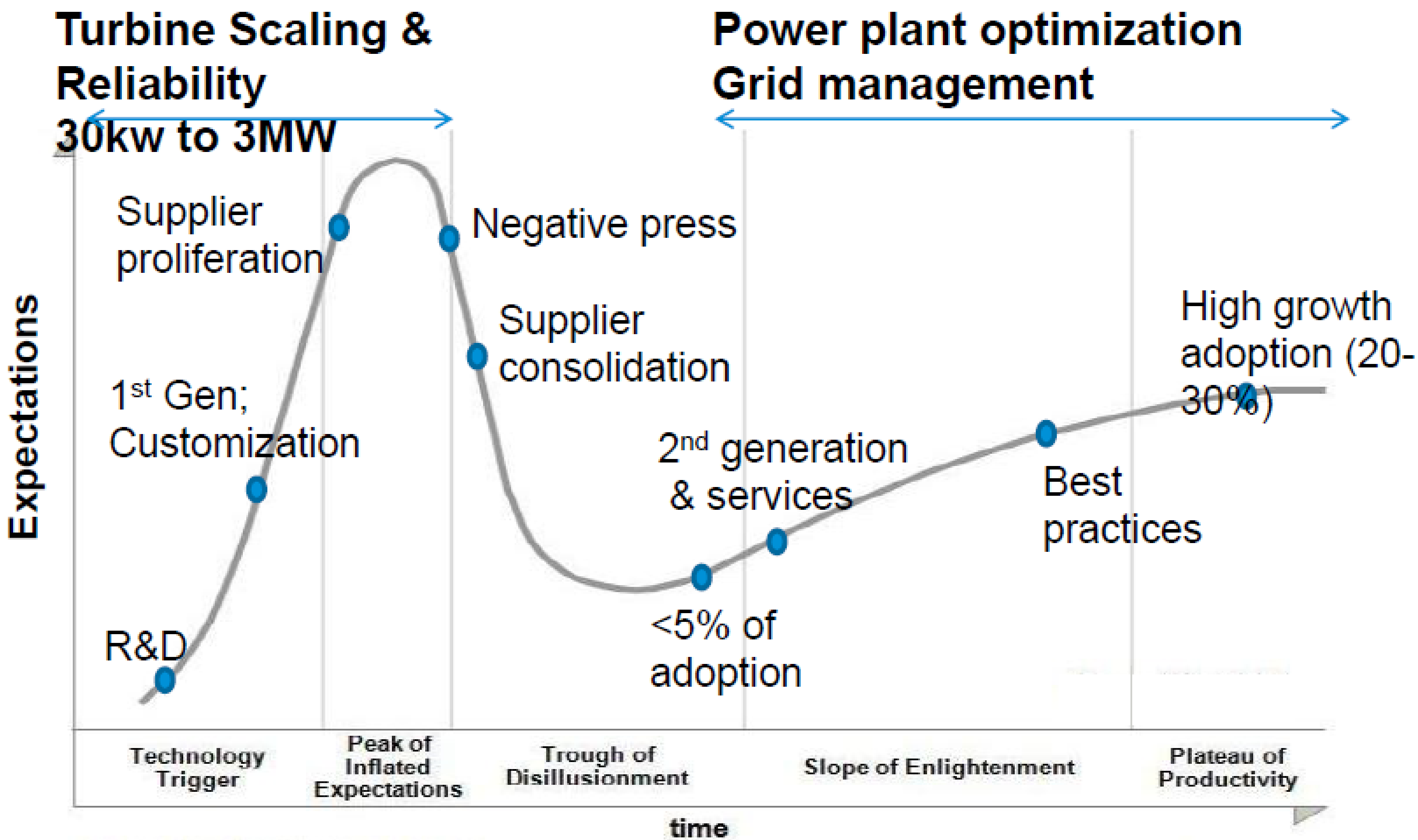
On the way up…

On the way *not* up…

participants becoming mature…

policy assistance shrinking…

# The curve of maturity…

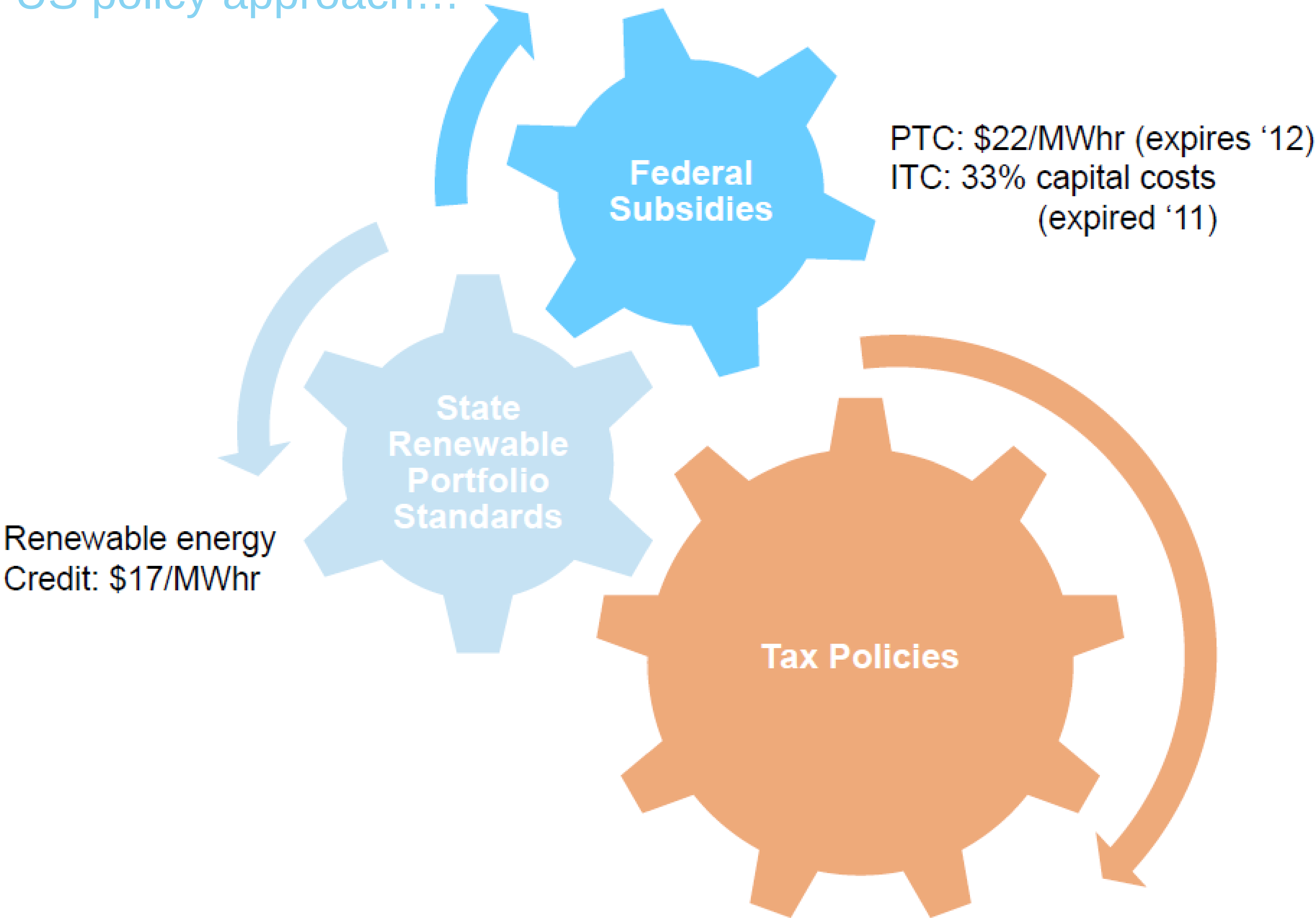



Source: Gartner´s hype cycle


# “Prostitution, horse racing, gambling and electricity are irresistible to politicians.”

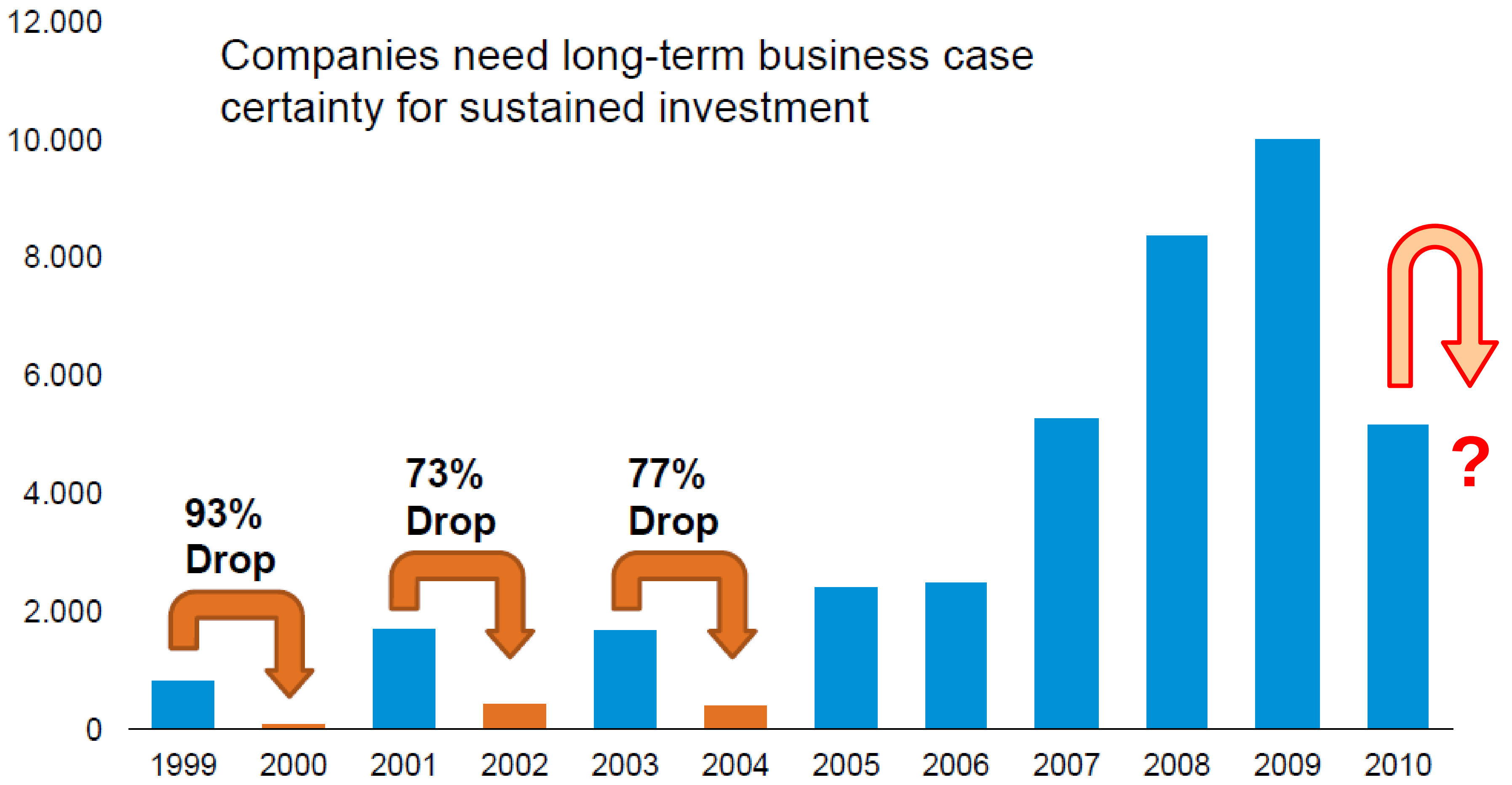
John Rowe, CEO of Chicago-based utility Exelon
*Wall Street Journa*l, Oct. 22, 2011

# US policy approach…



# Effects to the business…

Annual Wind Installed [MW]




Source: AWEA

Challenges with Wind

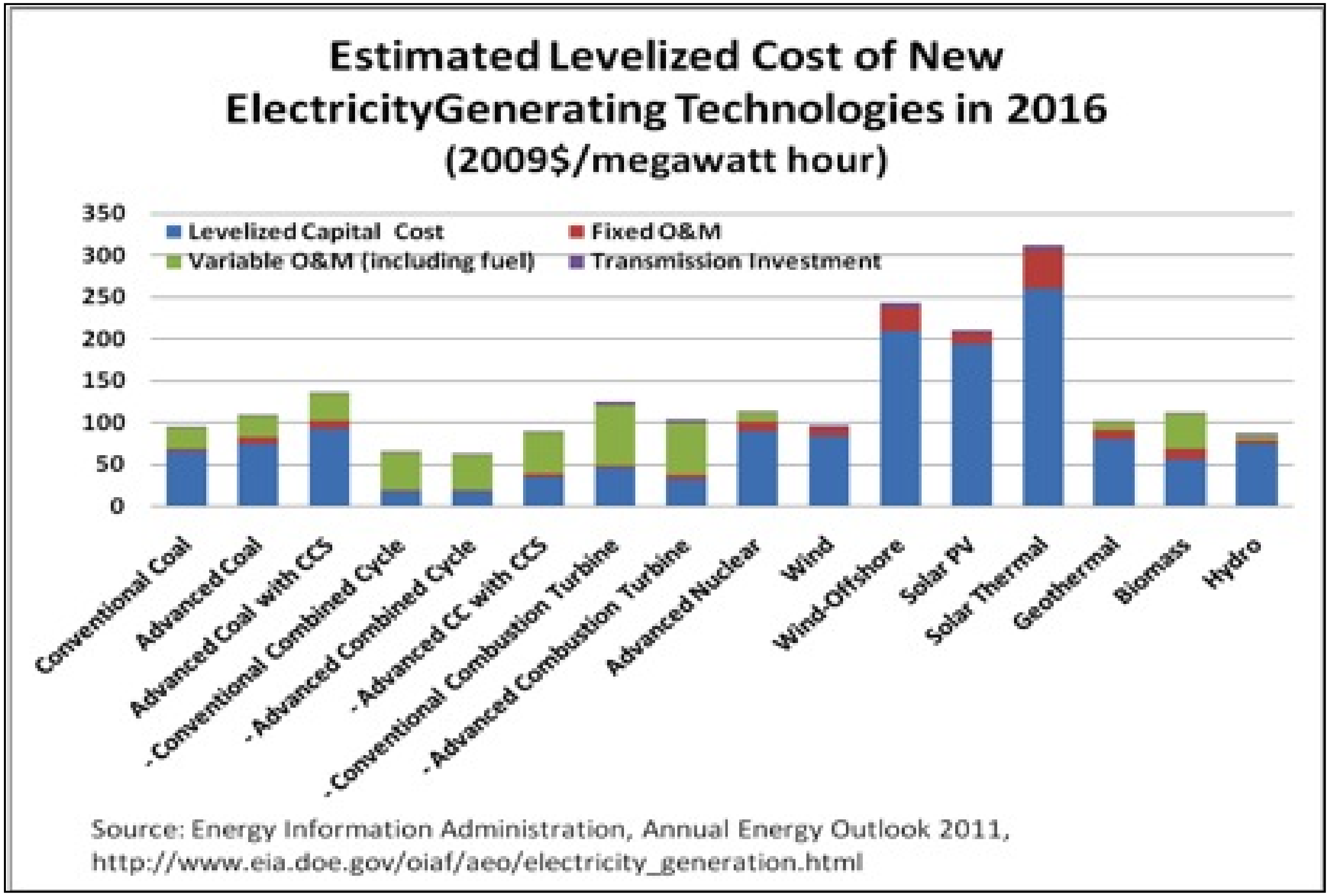
comparative LCOE

Opportunities with Wind

variability at grid interface

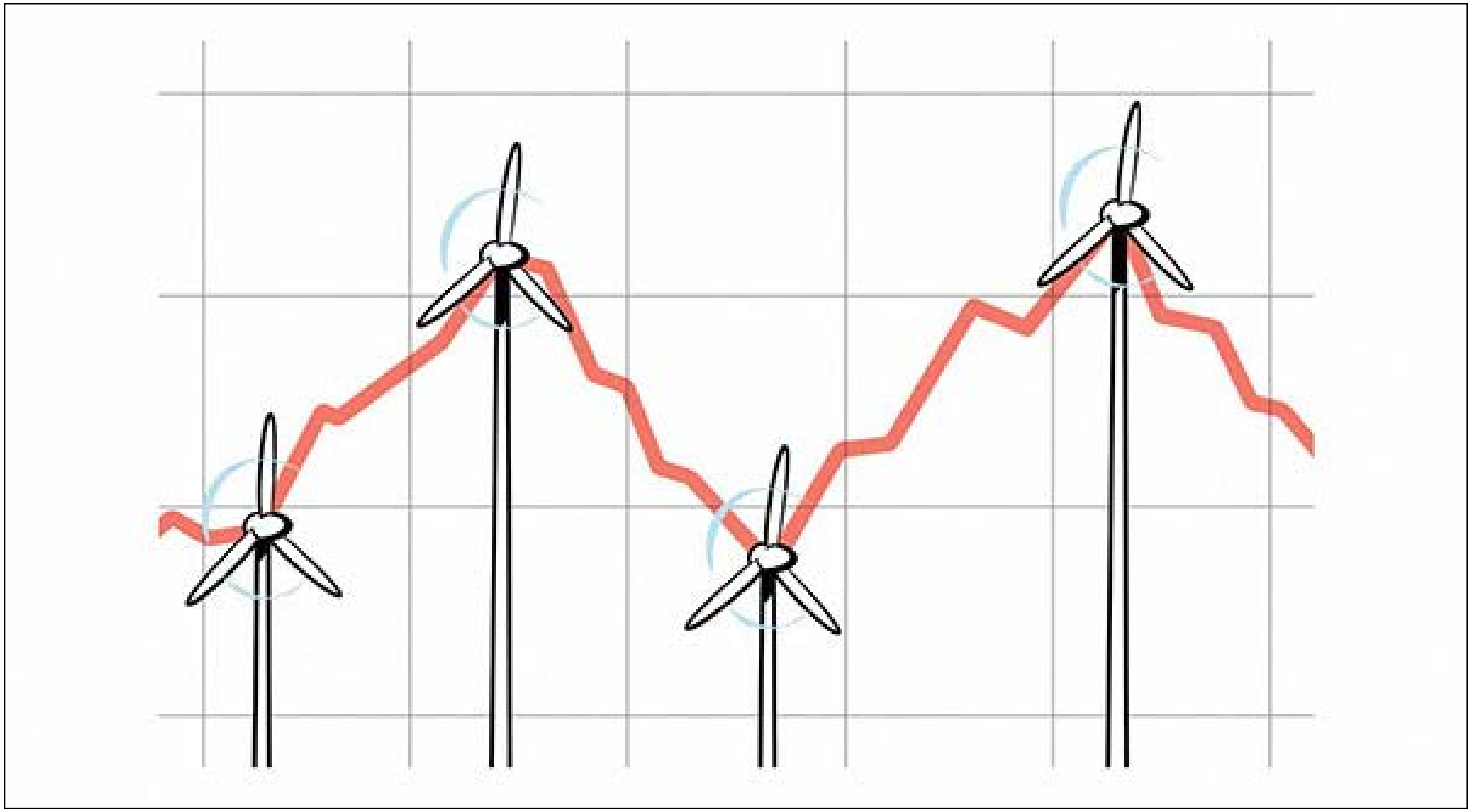
- Impediments for wide proliferation of wind assets are cost of wind generation (capital and maintenance), and risks associated with variability of wind (intermittency and unpredictability)

# Challenge 1: Levelized Cost of Energy




- Wind industry participants have been focused on selling turbines in the PPA market
- Financial models are based on double digit EBIT through high contribution margins
- Elimination/reduction of PTC for renewable generation will limit contribution margins
- Way to profitability will be in making wind LCOE (w/o PTC) less than LCOE with gas
- Falling gas prices will further challenge competitive advantage w/ wind generation

# Challenge 2: Variability at Grid Interface

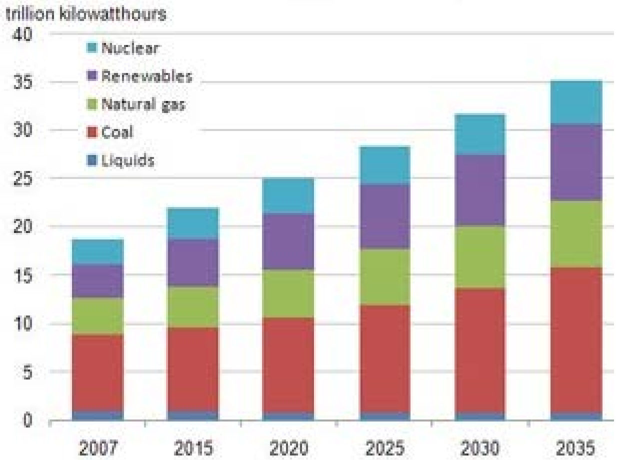


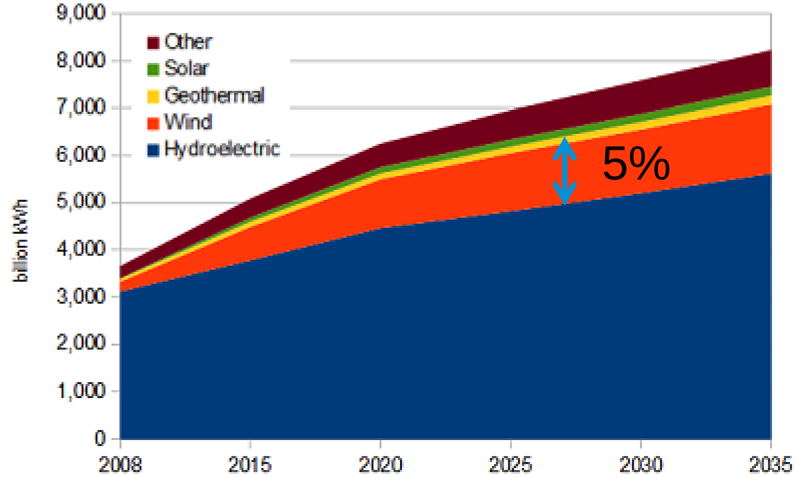
- Variability at grid interface is caused due to intermittency and unpredictability of wind
- Improved forecasting techniques quantify/limit the risks associated with variability
- Energy storage relieves short term variability, however increases system costs
- Low cost, high efficiency transmission (e.g. HVDC) further balances variability at grid

Challenges with Wind

Opportunities with Wind

reaching 20% proliferation




Source: EIA

Challenges | competitive LCOE | 5% | Opportunities

variability at grid interface

power transmission barriers

smart grid integration

15%


Besides cost of wind generation that will gain 5% market, impediments for wider (20%) proliferation of wind assets are variability of wind (unpredictability and intermittency), barriers for transmission (transportability), and compliance with smart grid infrastructure

PCS in Wind

components of a turbine

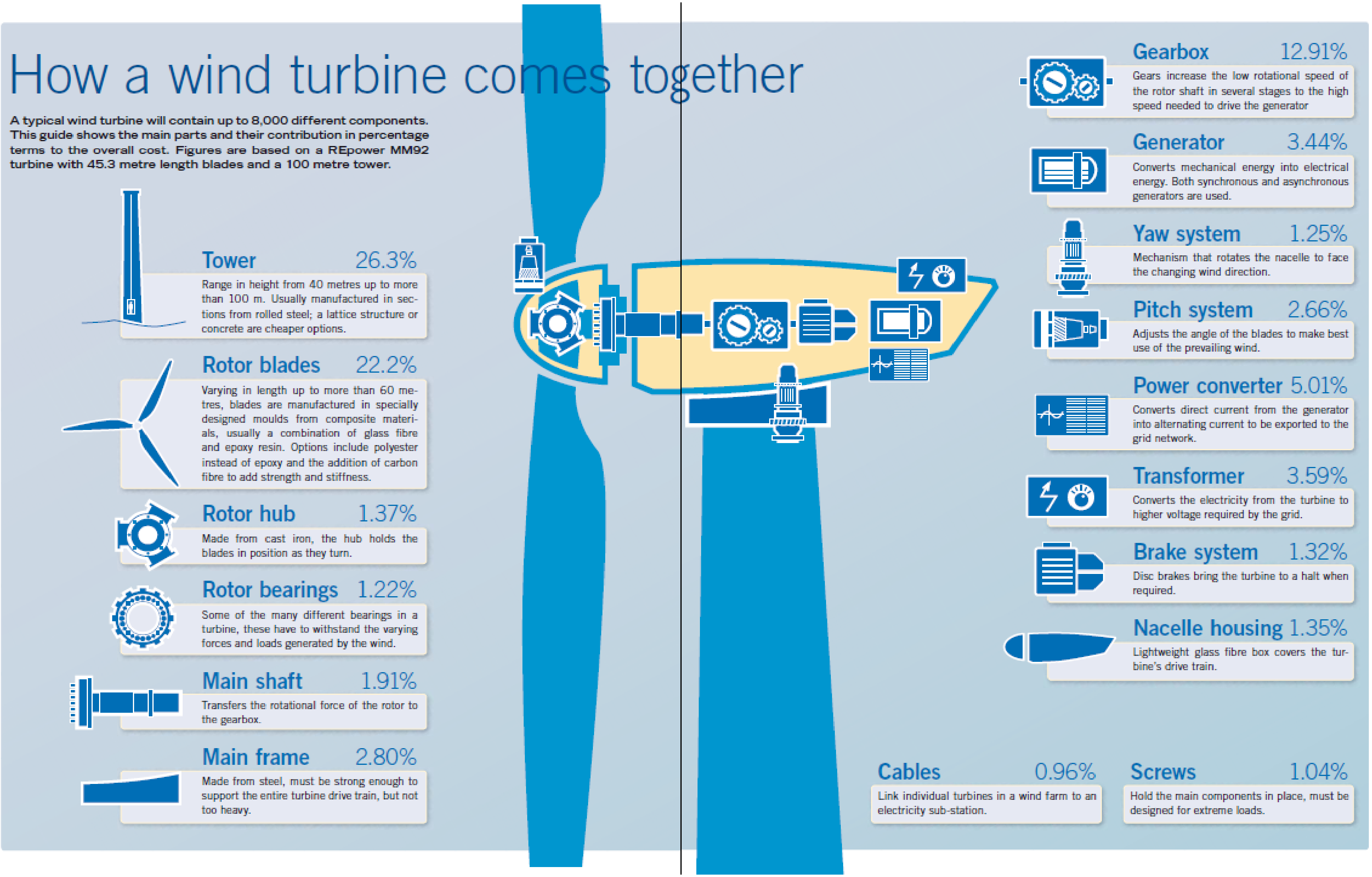
PCS in turbine

PCS in storage interface

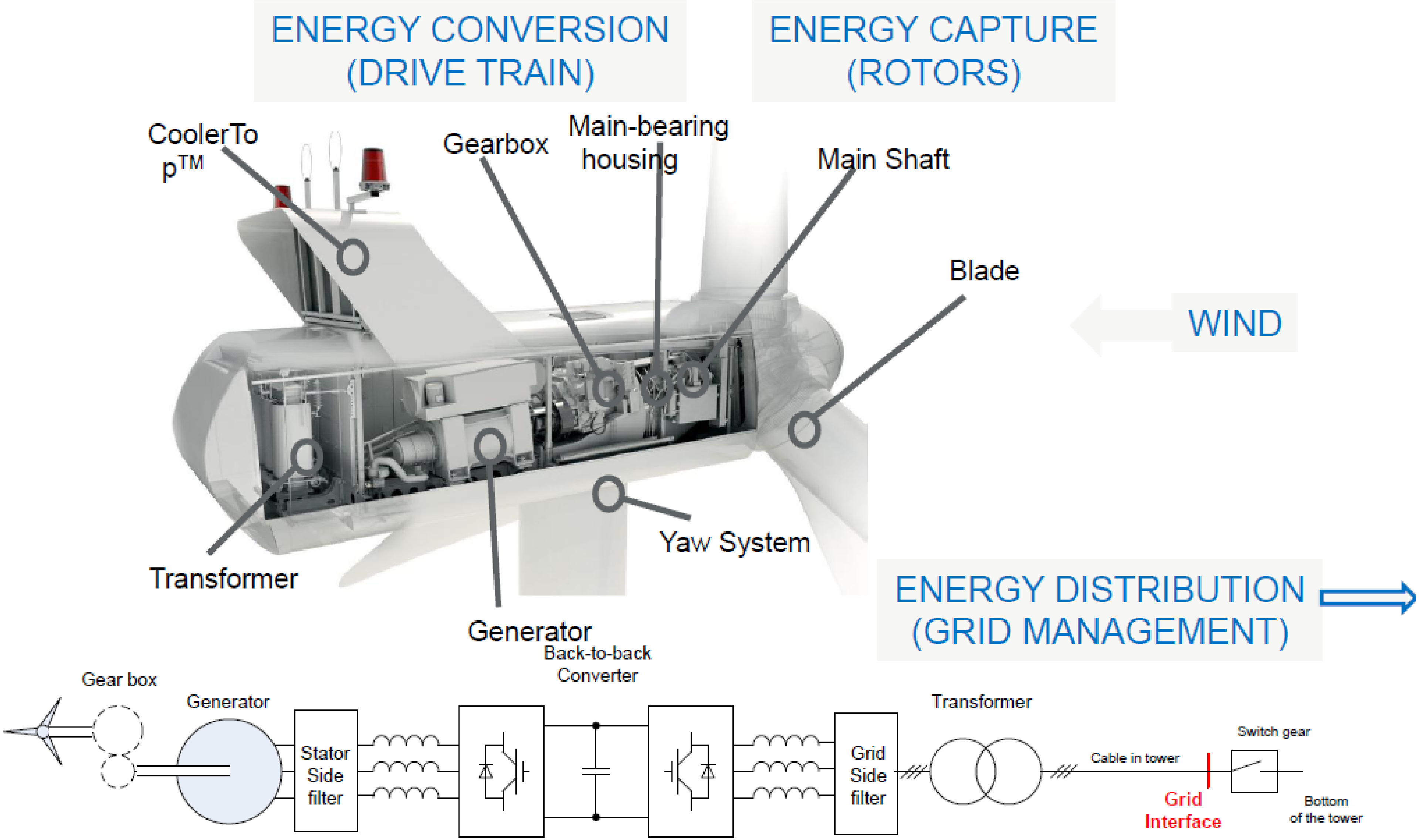
PCS in energy collection

PCS in power transmission

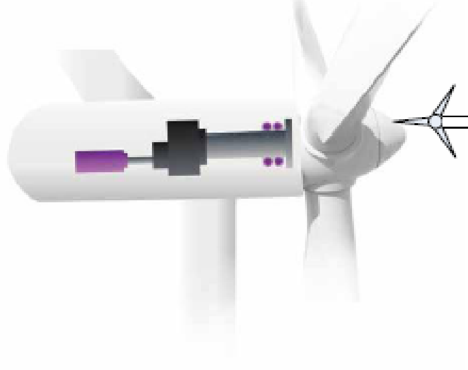
# Components of a turbine…

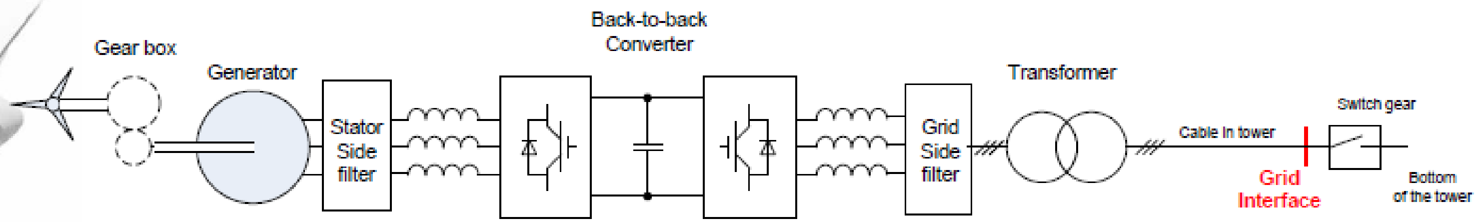


# Components of a turbine…



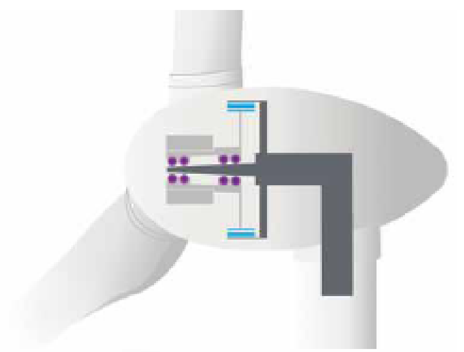
# PCS in a turbine…cost competitive conversion



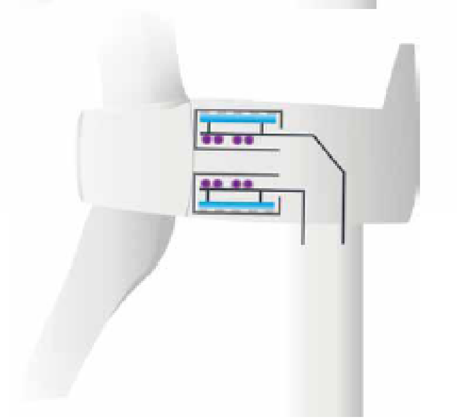



- Main drive train topologies and their advantages

| Geared | Gearless |
|---|---|
| Lower cost<br>Lower weight<br>Proven technology | High reliability (yet to be proven) |

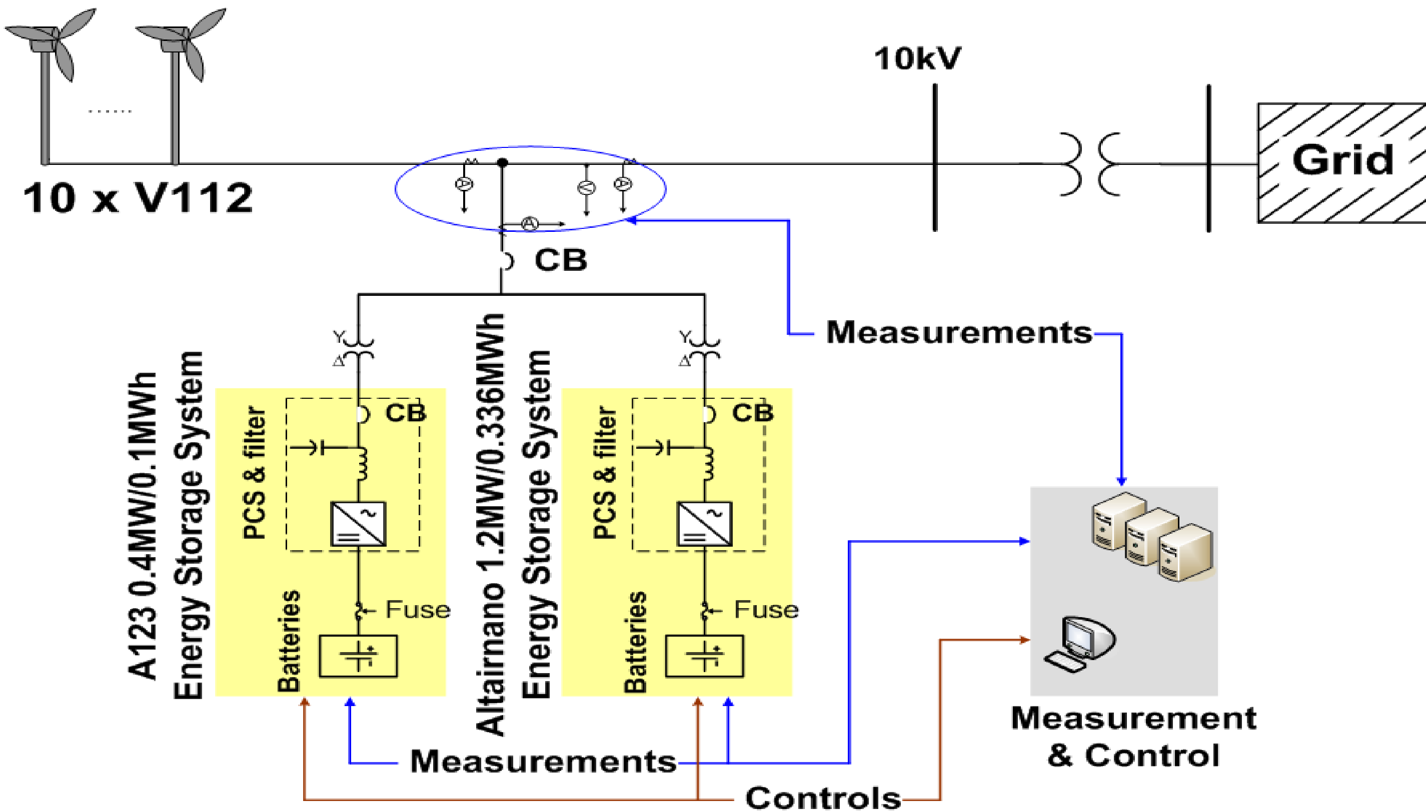


- The technology adoption will be influenced by
  - Cost
  - Reliability in very long term operation >20 years
  - Scalability > 10MW



- On-going R&D on power conversion topics
  - Crossover from low voltage to medium voltage to HVDC
  - Do not use power electronics all together? E.g. hydraulic transmissions with synchronous generators coupled to the grid.

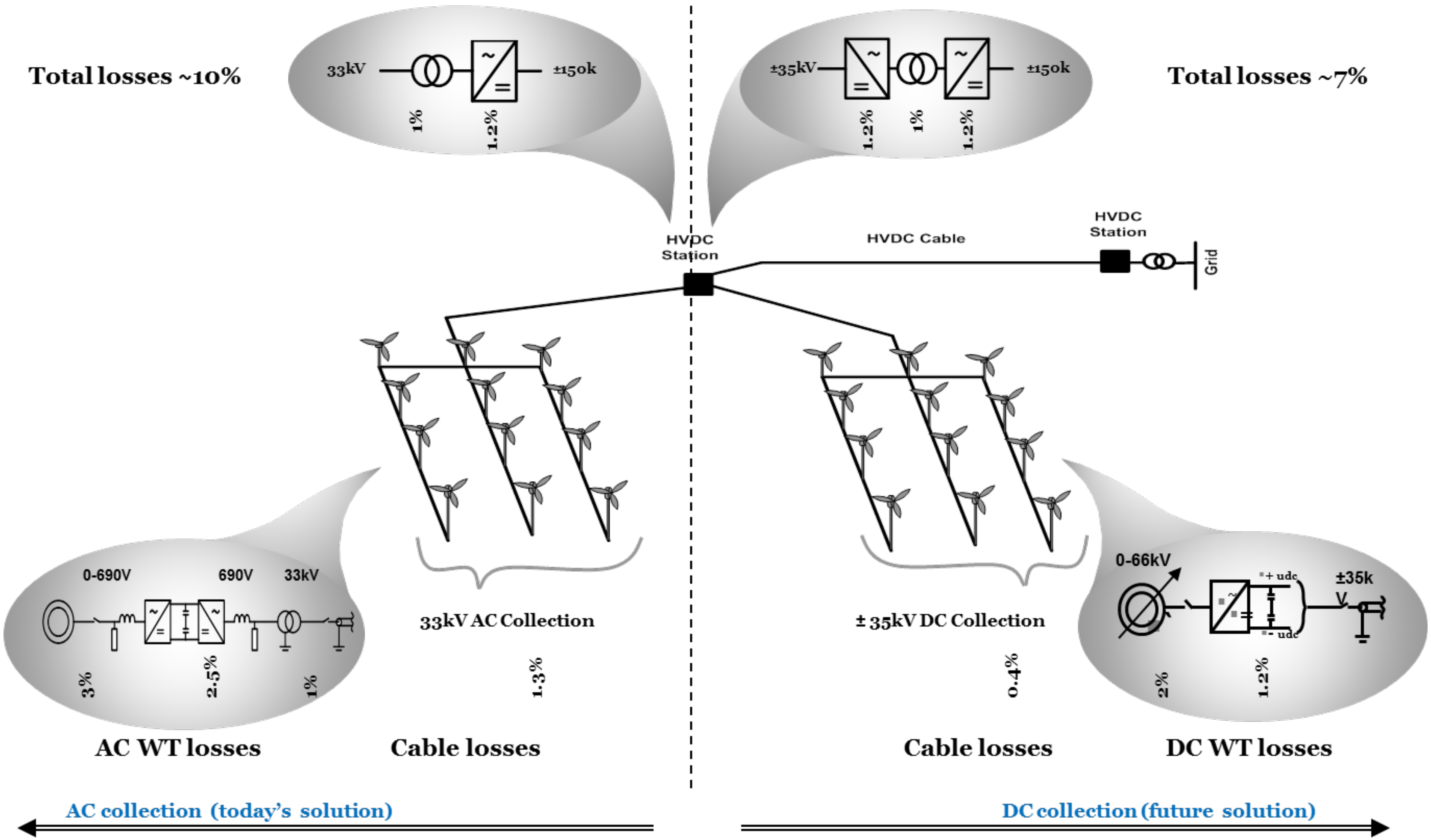
# PCS in energy storage interface…cost effective invariability





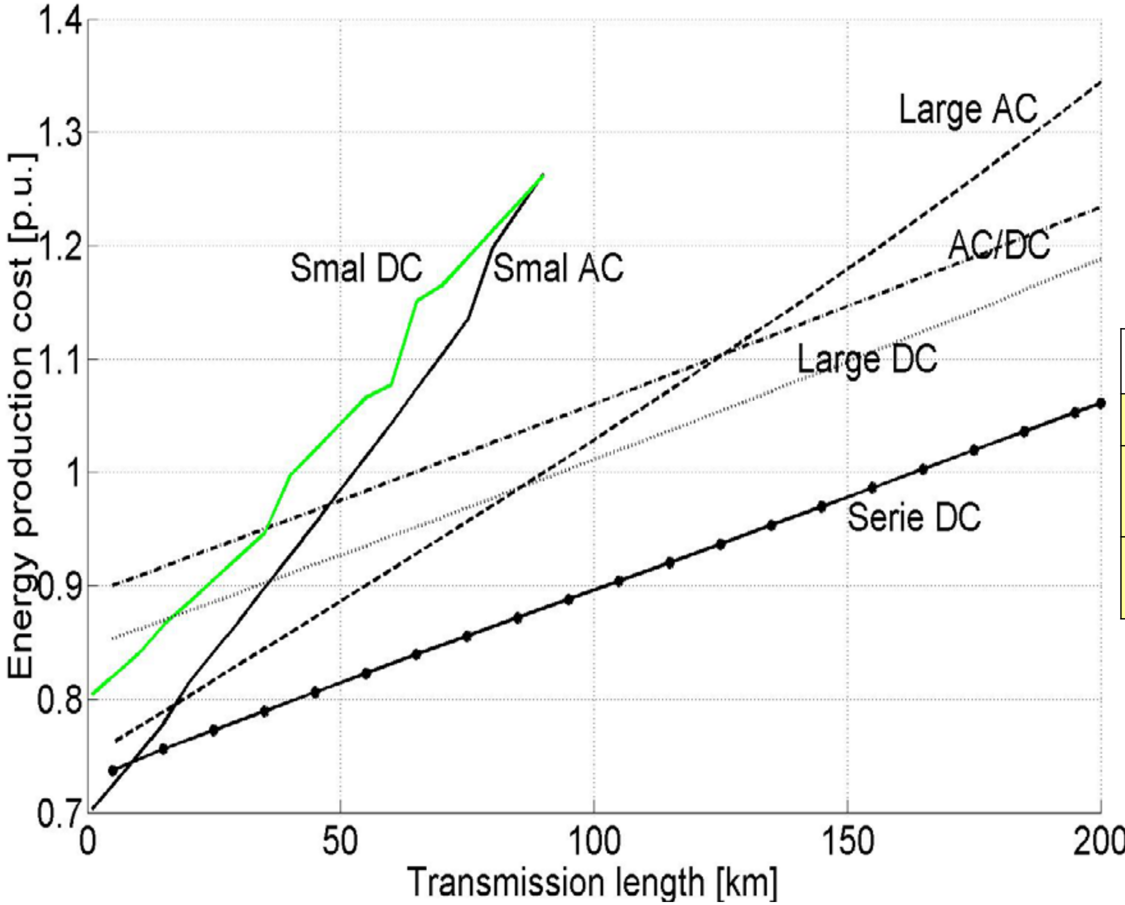
- 1.6MW energy storage combined with 30MW wind power plant
- Offers energy buffer for wind to participate in ancillary services market
- Challenge is in making the system attractive from RoI perspective

# PCS in energy collection…maximize efficiency




DC turbines combined with DC collection has a potential to offer up to 30% improvement in reducing energy losses. This improvement is obtained through reduction of turbine-side and station-side converters. However, the challenge is in realizing such high power DC/DC converters.

# PCS in power transmission…maximize power plant AEP




| Vestas Offshore Options | |
|---|---|
| ***Current (HVAC)*** | ***Future (HVDC)*** |
| High Losses | Low Losses<br>Reactive power not required |
| High Costs | Low Costs<br>One less cable + converter |

HVDC is appearing to be the technology of choice to transport power from wind power plants over long distances (e.g. from deep water offshore to onshore). However, significant challenges are in protection and control of such DC architectures.

Bob

Reedy

# *Driven by the Sun --"Powerful" Thoughts on PCS Development*

Brief Information and Opinions

NIST May 2012

Bob Reedy
+1.321.638.1470
reedy@fsec.ucf.edu

# *Future Grid– Gotta Happen, Gonna Happen:*

- Back-to-Back DC links inserted in major AC ties
- New major Transmission is DC
- Widely dispersed DG (primarily solar)
- Reactive power control via PCS
- Ancillary services via PCS
- Improved System Stability
- Resistance to Fault Induced Delayed Voltage Recovery (FIDVR)

***Behold: The "asynchronization" of the Grid….***

# Why?

COST

RISK

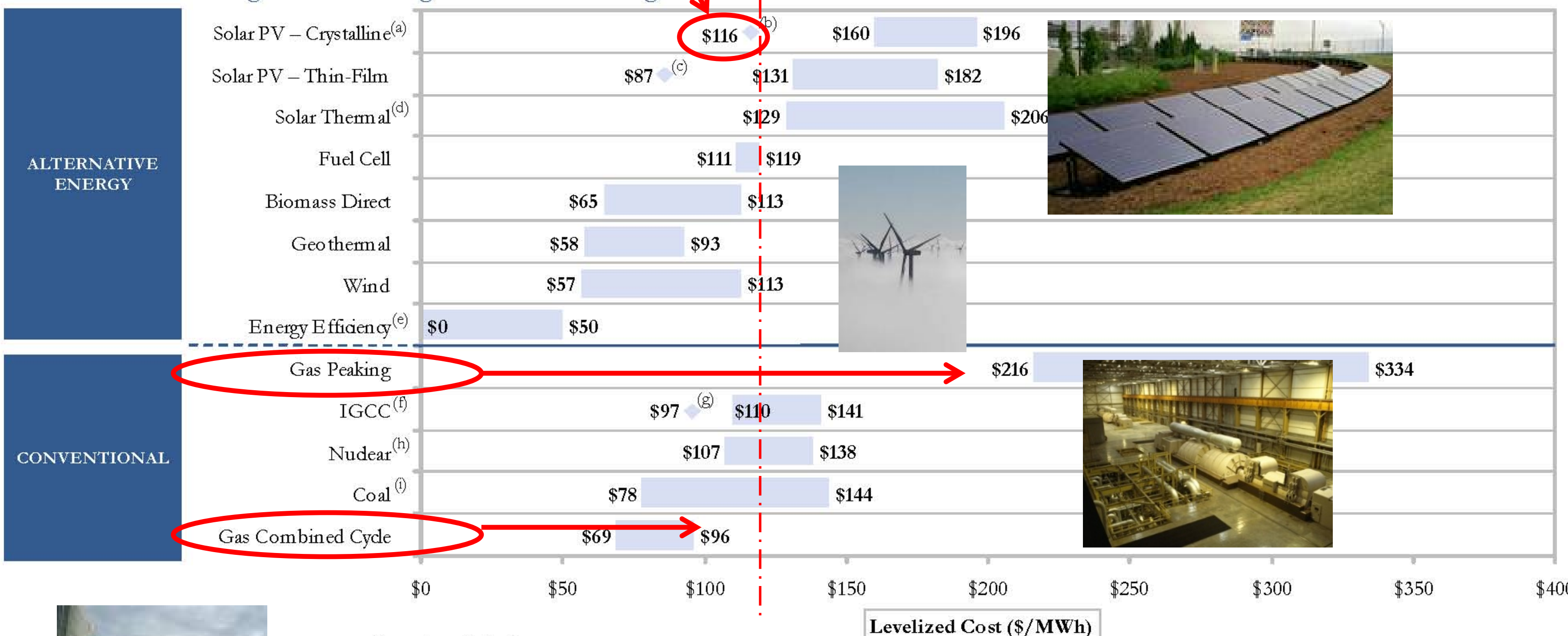
# --So Energy Cost will not be the key determinant in PV penetration



2009 Study – Today we are HERE – (with really cheap gas!)

## Levelized Cost of Energy Comparison

Certain Alternative Energy generation technologies are becoming increasingly cost-competitive with conventional generation technologies under some scenarios, before factoring in environmental and other externalities (e.g., RECs, potential carbon emission costs, transmission and back-up generation/system reliability costs) as well as construction and fuel costs dynamics affecting conventional generation technologies




*Source: Lazard estimates.*

Note: Reflects production tax credit, investment tax credit and accelerated asset depreciation, as applicable. Assumes 2008 dollars, 20-year economic life, 40% tax rate and 5-20 year tax life. Assumes 30% debt at 8.0% interest rate, 40% tax equity at 8.5% cost and 30% common equity at 12% cost for Alternative Energy generation technologies. Assumes 60% debt at 8.0% interest rate and 40% equity at 12% cost for conventional generation technologies. Assumes coal price of $2.50 per MMBtu and natural gas price of $6.00 per MMBtu.

(a) Low end represents single-axis tracking crystalline. High end represents fixed installation.
(b) Represents estimated implied levelized cost of energy in 2012, assuming a total system cost of $3.50 per watt for single-axis tracking crystalline.
(c) Represents a leading thin-film company's targeted implied levelized cost of energy in 2012, assuming a total system cost of $2.00 per watt.
(d) Low end represents solar tower. High end represents solar trough.
(e) Estimates per National Action Plan for Energy Efficiency; actual cost for various initiatives varies widely.
(f) High end incorporates 90% carbon capture and compression.
(g) Represents estimated implied levelized cost of energy for Southern Company's proposed IGCC facility in Mississippi that is expected to be in service in 2013, assuming a total system cost of $3.00 per watt and 50% carbon capture, per Southern Company public comments.
(h) Does not reflect decommissioning costs or potential economic impact of federal loan guarantees or other subsidies.
(i) Based on advanced supercritical pulverized coal. High end incorporates 90% carbon capture and compression.



KUDOS

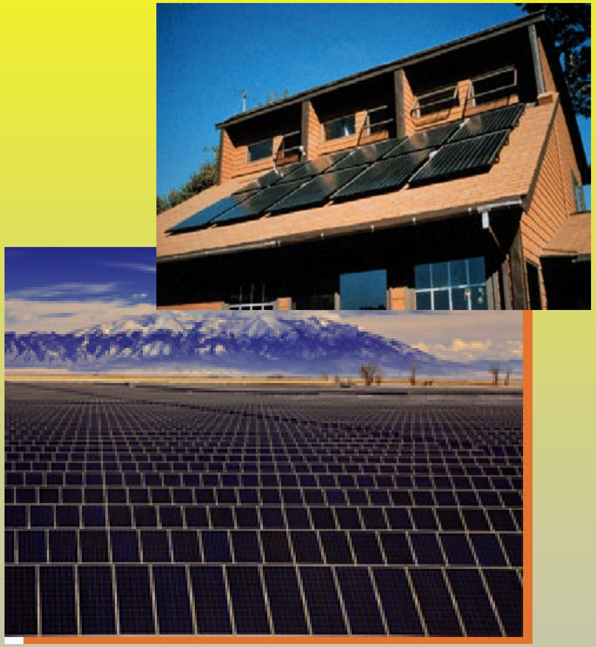
# *Why PV?*

- No Fuel
- No O&M
- Mostly capital – rate based (IOU), bond finance (public power)
- Incremental Commitments (low risk)
- No/low land issues
- No/low aesthetic issues

# *Why PCS at Transmission Level?*

- Realities of Reactance
- Realities of ROW
- Realities of Reliability
- Realities of Retrofit

# *Way Better than Today*



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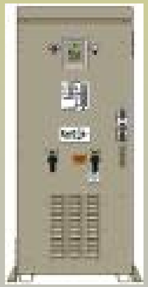
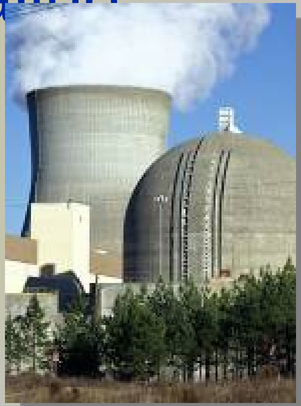


Advanced Communications & Control of Inverters to Enable PV to Behave like Conventional Generation

*"WLAD"*

# *Given High Power PCS at Transmission Level, Note:*

- Distributed Systems can have same characteristics
- DG can/will be centrally controlled, but with highly autonomous powers
- Distributed PCS can/will replace capacitors, regulators
- A truly coordinated, inherently stable, self-healing grid



# "The Solar Effect"

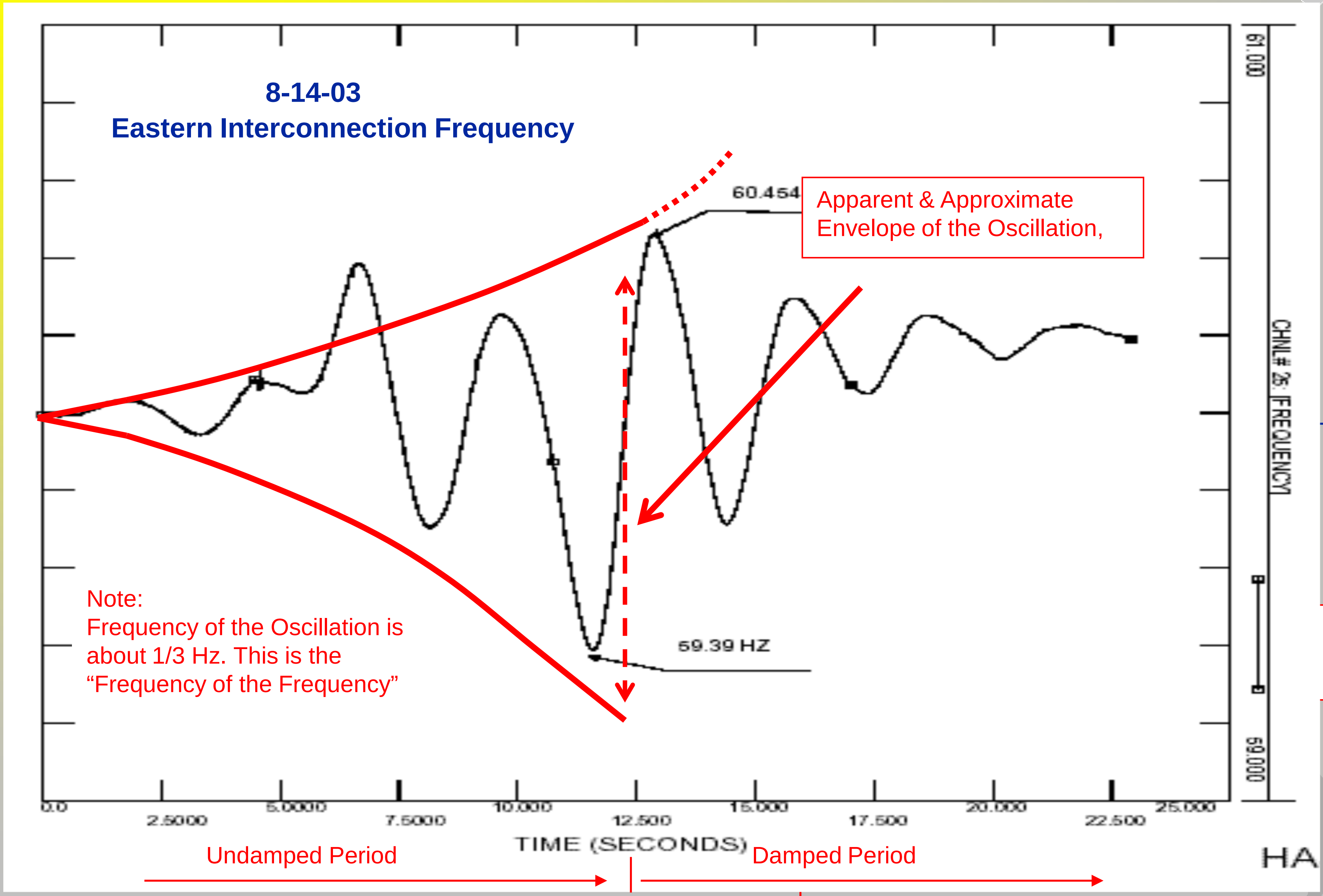
- Lower PV costs drive
- Lower/Better PCS (beginning with inverters), driving lower cost
- For PCS throughout the Grid…..

# (at the) Florida Solar Energy Center

*Creating Energy Independence Since 1975*

A Research Institute of the University of Central Florida

# A HUGE Argument for Doing It!



Kyle

Clark

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**Workshop on High Megawatt Electronics:**
**Technology Roadmap Workshop for Increased Power Electronic Grid Applications and Devices**
**May 24, 2012**

# Power Conversion System Architectures

## For Grid Tied Energy Storage

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Kyle Clark

DYNAPOWER COMPANY

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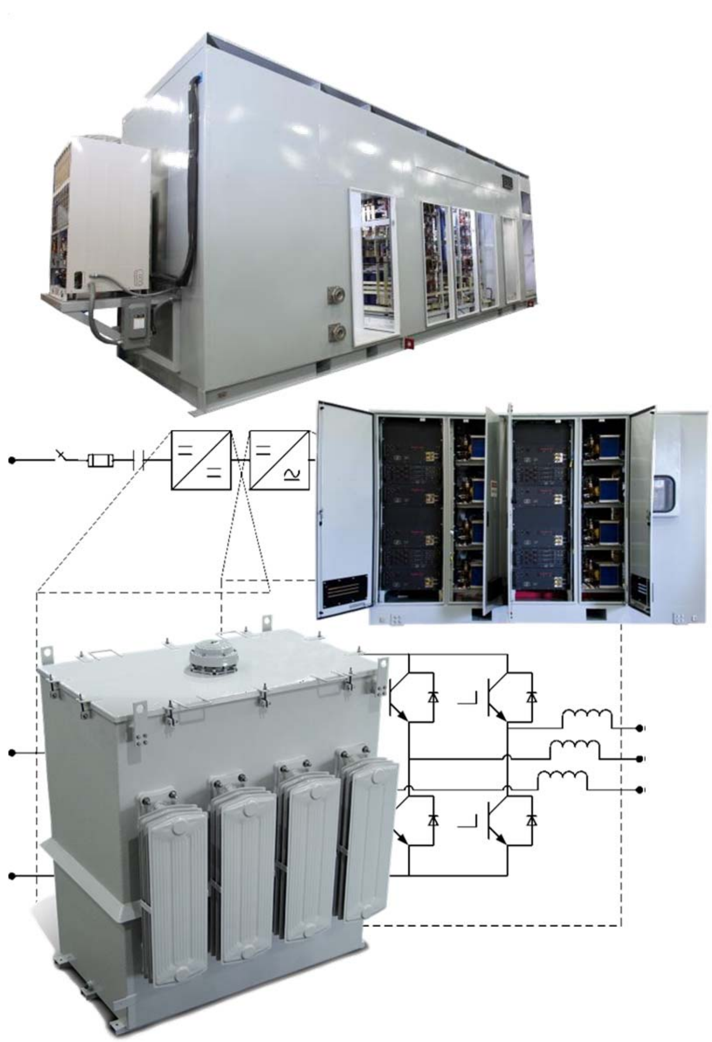
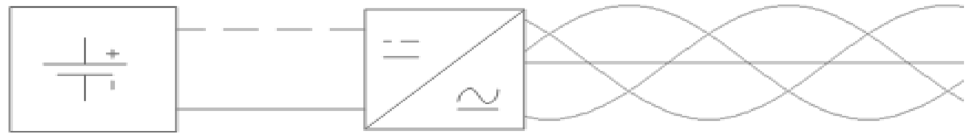
# Outline



1. Power Conversion System (PCS)
   – Overview and Purpose
2. Conversion Topologies
   – Single Stage three-legged IGBT based inverters
   – Multi-stage converters
   – Inverter Operation
   – Advanced Topologies
     • Multi-level inverters
     • Z-inverters
   – Multiple Module Topologies
3. Application Topics
   – Increasing Power Levels
     • Line Commutated Inverters
   – Islanding methods
   – Phase Configuration
   – Transformers for Energy Storage Systems (ESS)

• Output power compliance

# PCS Overview and Purpose



Grid Tied Energy Storage mediums are predominately direct current (DC) in nature. To effectively utilize the energy storage capacity on the present electric utility grid, the energy must be converted to a standard Alternating Current (AC) level and regulated through a converter.

Converter Purpose and Control:

- Bi-directional conversion from AC to DC and DC to AC.
- AC Grid to DC Storage isolation and protection
- Interconnection and control of multiple DC Sources
- Regulated, stable and controllable power flow

Control Modes

- AC current (P,Q) – Standard Grid Tied Operation
- AC Voltage (V,F) – Islanded Operation
- DC current ($I_{DC}$) – Grid Tied, Battery Charge/Formation
- DC Voltage ($V_{DC}$) – Grid Tied, Battery Conditioning

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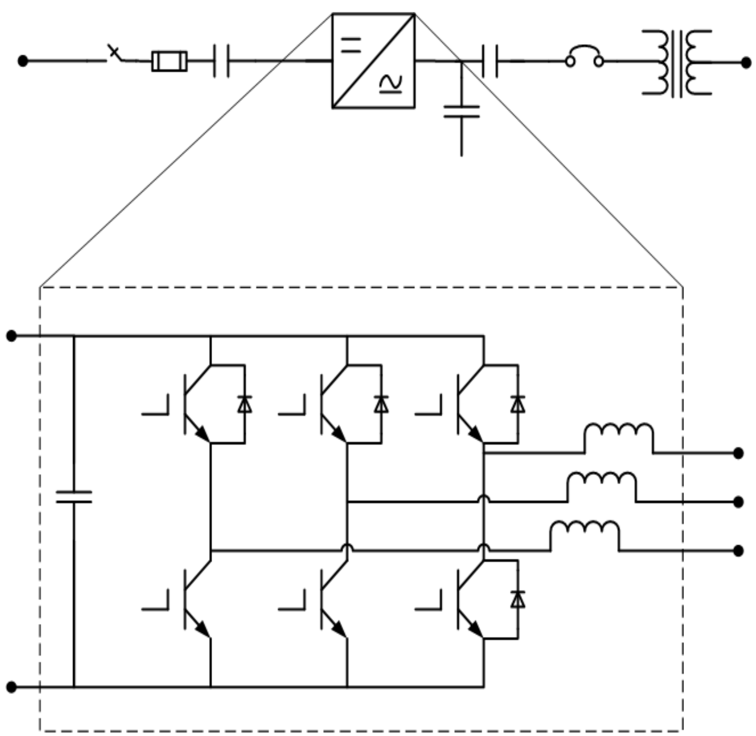
# Basic AC/DC Power Conversion Topologies

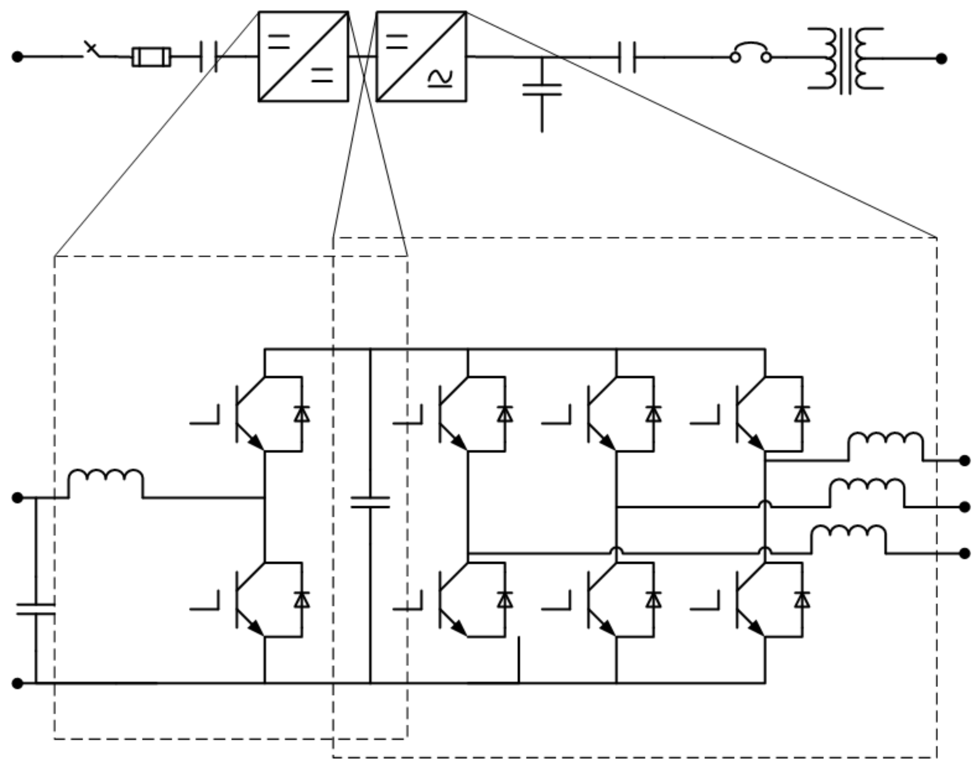
## Single Stage Converters

- Limited to DC Voltages > 1.5X $VAC_{RMS}$
- Maximum Efficiency



## Multi-Stage Converters

- Maximum DC Voltage Range
- Increased Losses
- Increased hardware Cost



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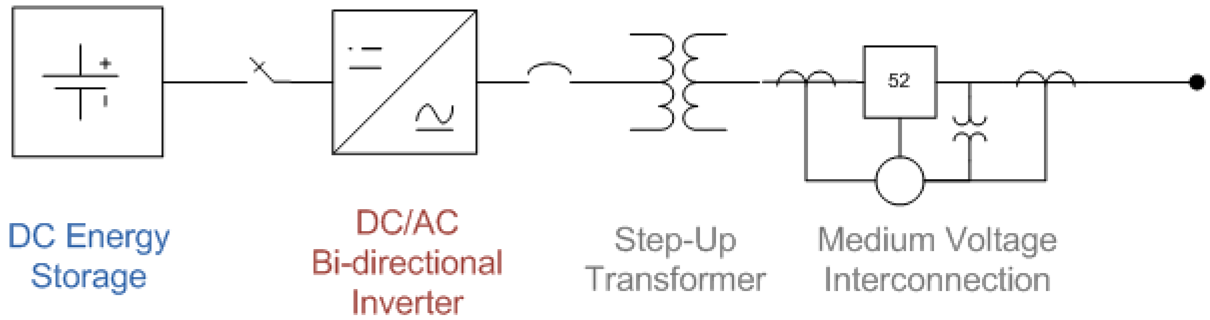
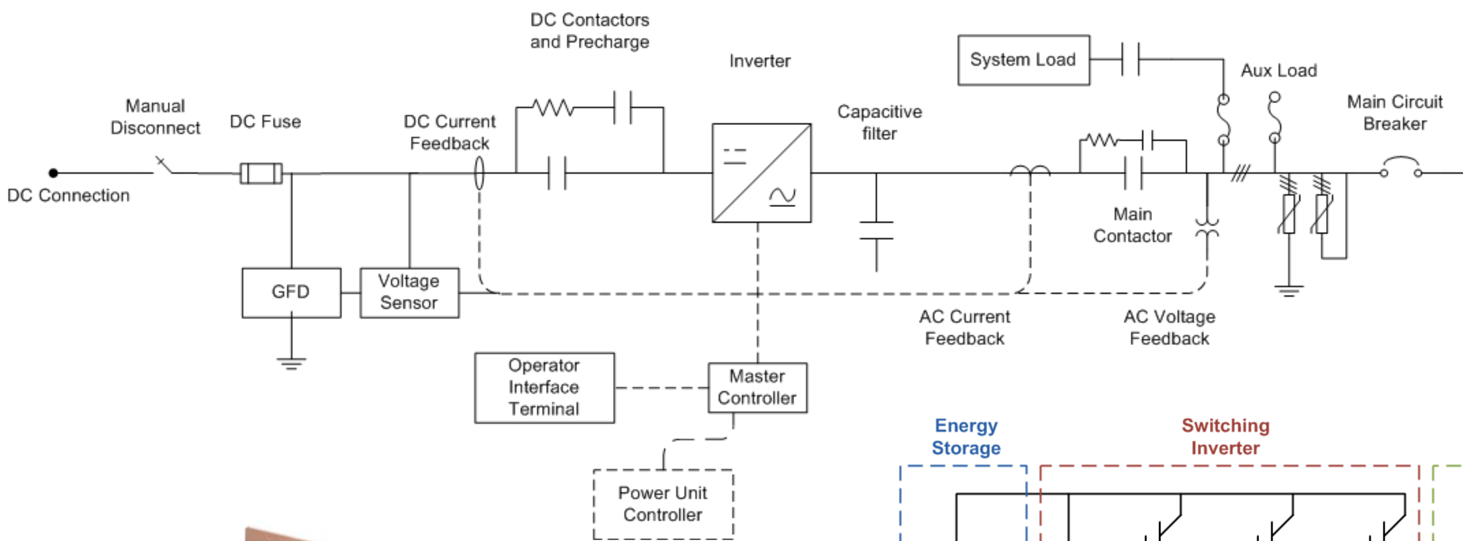
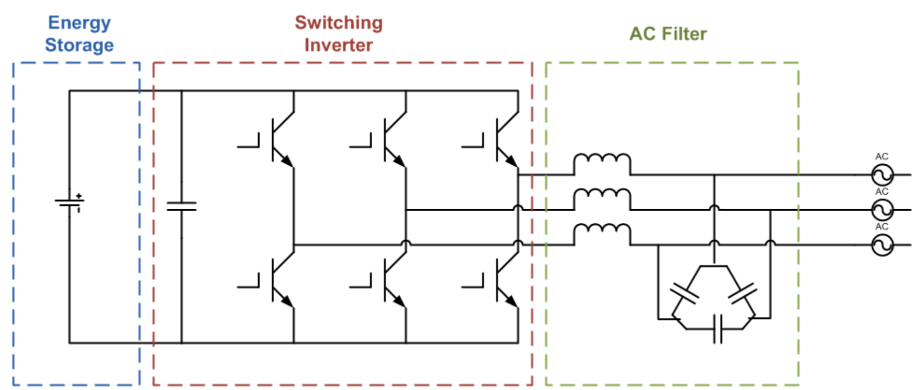
# Single Stage Inverter

## Primary Sub-Sections

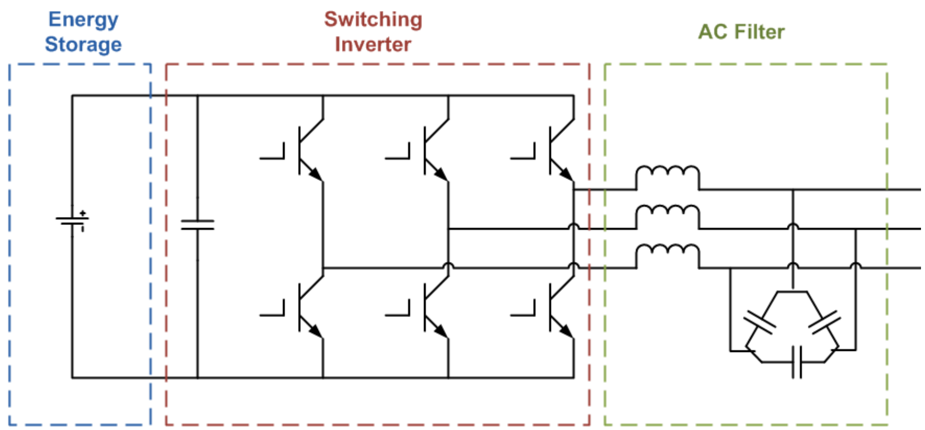


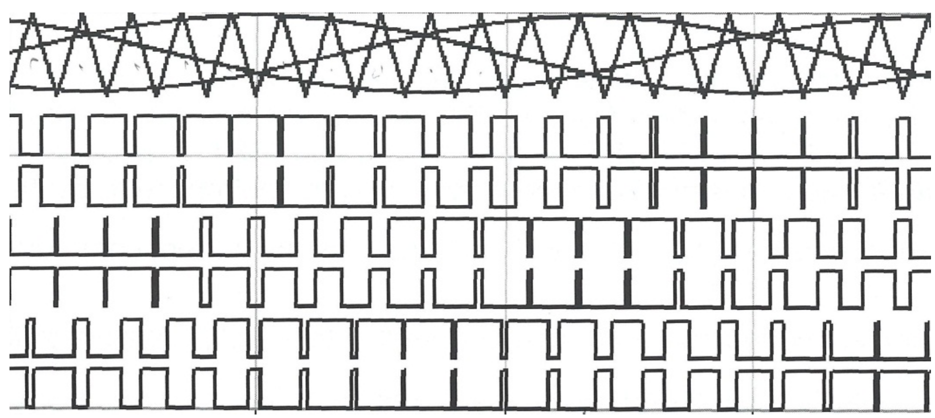




# Basic Inverter Operation

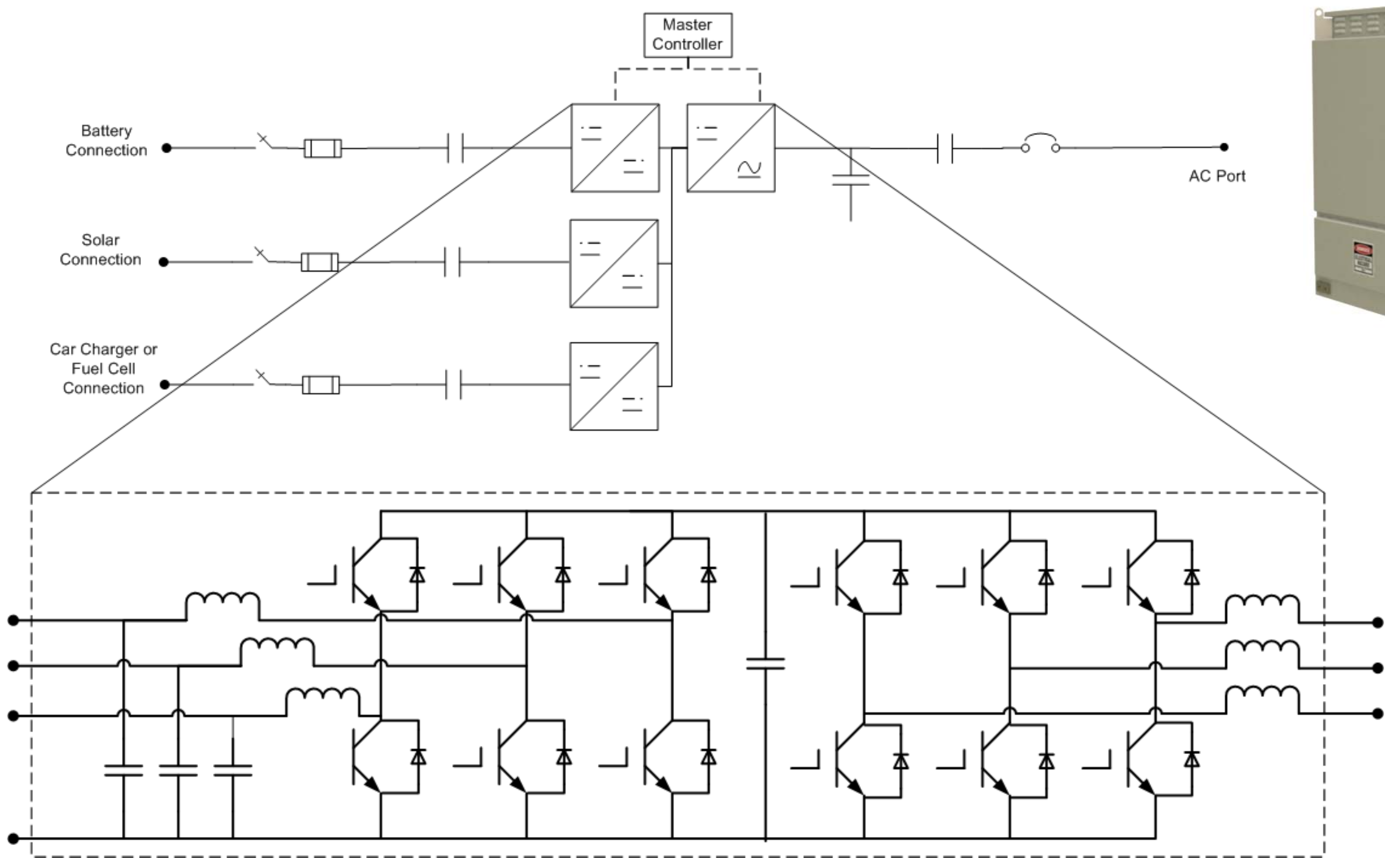
- Operation
  - Sinusoidal Pulse Width Modulation
  - Phase locked to Grid
  - Reference signal provided to compare with triangle waveform
  - Gates are triggered as output of controller
  - Modulation is provided to control power
  - Output is filtered to provide limited harmonics/switching noise



# Advanced AC/DC Power Conversion Topologies

- Multi-Port, Multi-Stage Converter
  - Optimized for renewable integration with energy Storage

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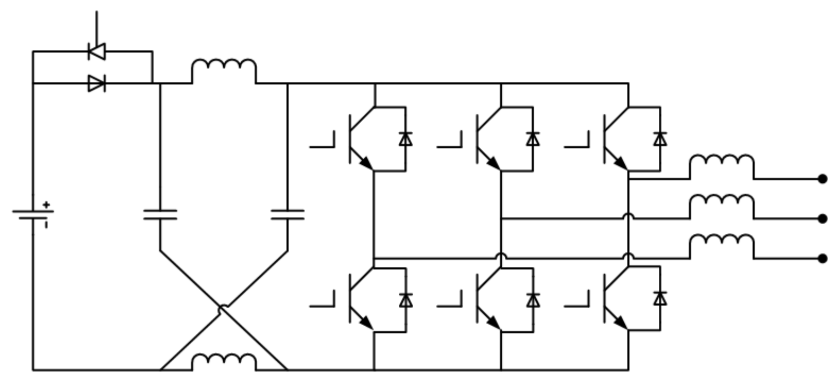
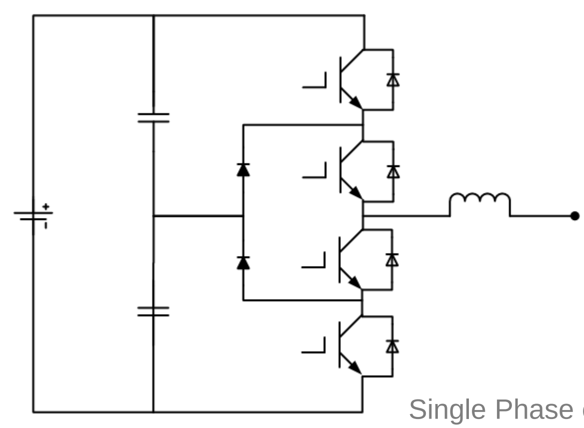
# Other Advanced Inverter Topologies

- Z-inverter
  - Accommodates reduced DC voltages (boost DC > AC)
  - Inherently protected by limiting DC current



- Multi-level inverters
  - Increased DC and AC voltages
  - Reduced Losses
  - Reduced Harmonics, smaller filters
  - Requires special $V_{iso}$ IGBTS

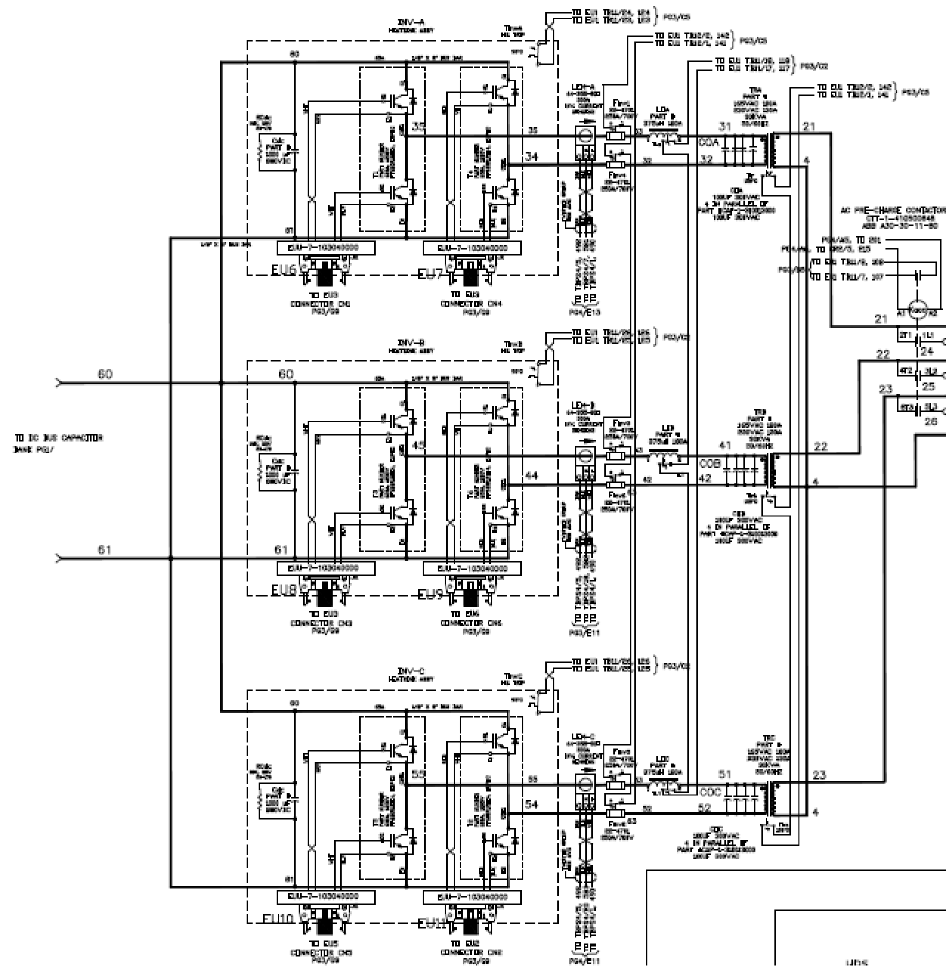
(Diode Clamped, Flying Capacitor and Cascade Multi-Level Cell)



Single Phase of Diode Clamped Three Level Inverter

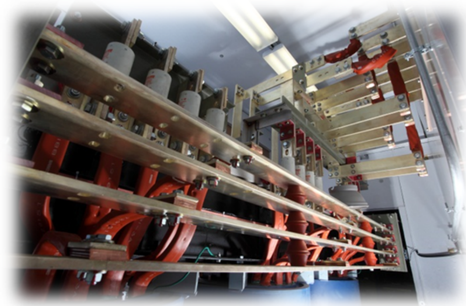
# Independent Phase Control Systems

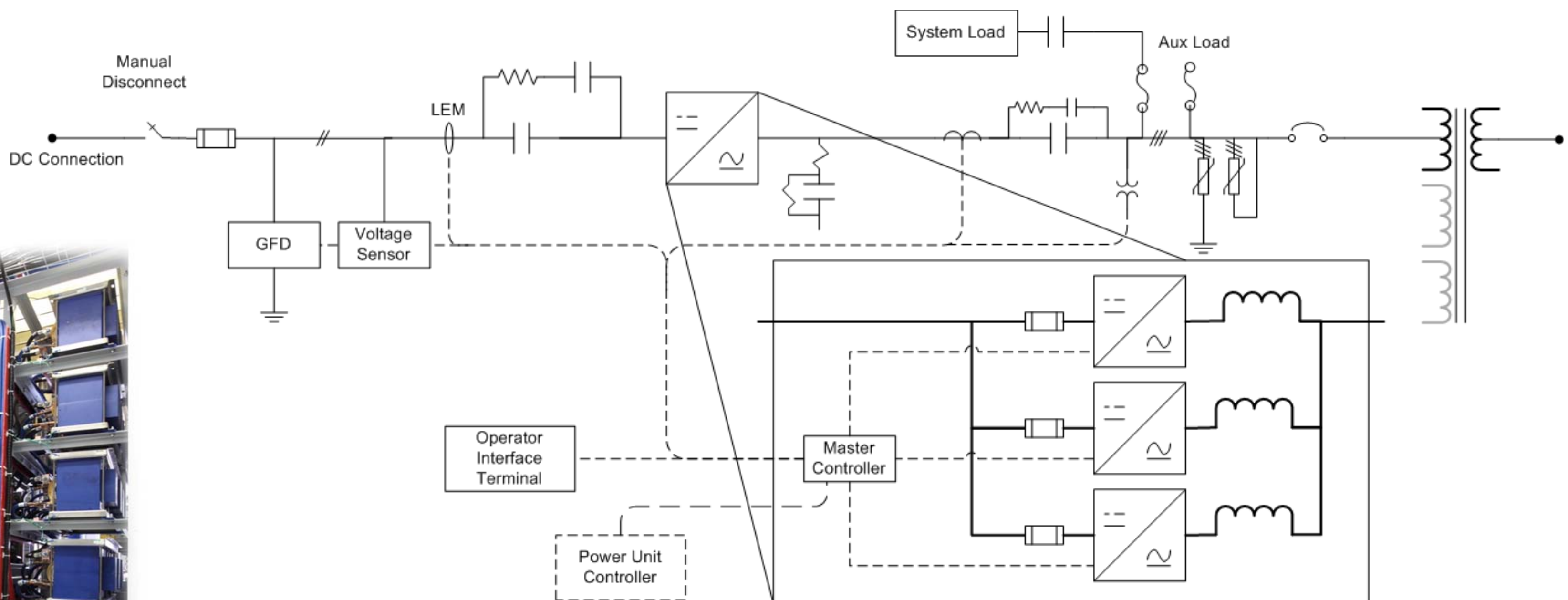
- Independent Phase control
  - 240 VAC Split Phase
  - Three Phase systems
  - Grid Stabilization and Balancing
  - Single or independent Battery strings



# Multiple Module Topology

- For Multi-MegaWatt Systems
- Redundant Parallel N+1 Configurations
- Synchronous and Interleaved Switching
- Independent Battery Strings



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# Increasing Power Levels for ESS

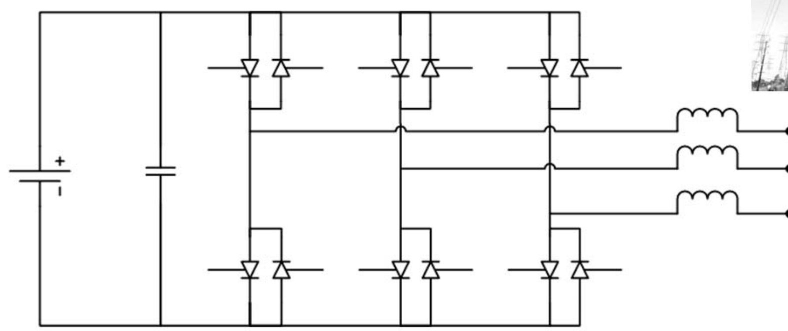
**Parallel, Multi-module IGBT based Inverter Systems**

- Sub-Cycle response
- True 4 quadrant operation
- Low harmonic levels

**Thyristor Based Line Commutated (Cycloconverter) Systems**

- Reduced cost per $/MW
- Limited power factor control
- Large AC Filters Required
- Increased Response Time
- Hybrid Systems

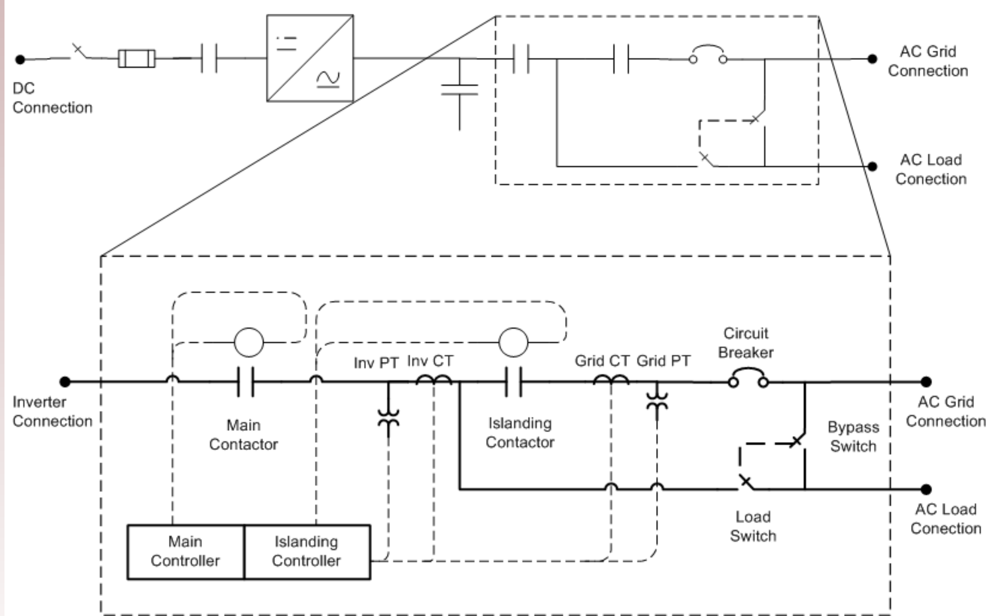
1.5MW Inverters installed at Xtreme Power BESS in Hawaii



# ESS Islanding Methods

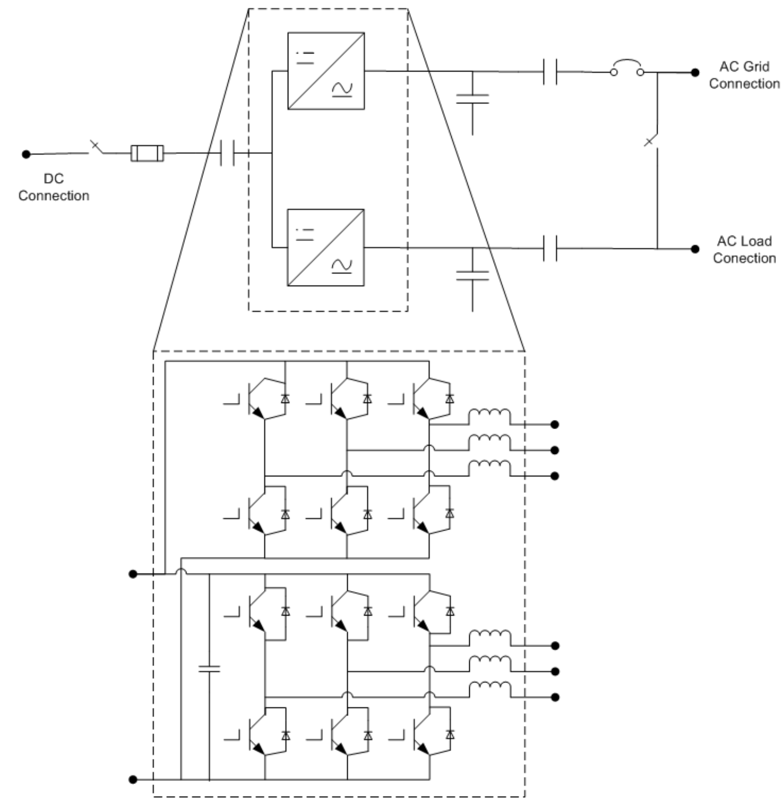
## Offline ESS with Dynamic Transfer (Islanding)

- Maximum Efficiency
- Minimum components
- Minimum Losses




## Online Double Conversion

- Limited to PCS Power to load
- 2X conversion losses
- Increased Complexity



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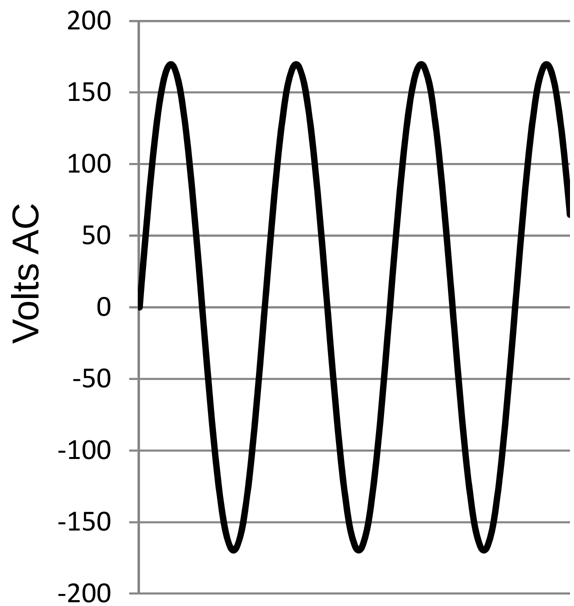
# Phase Configuration

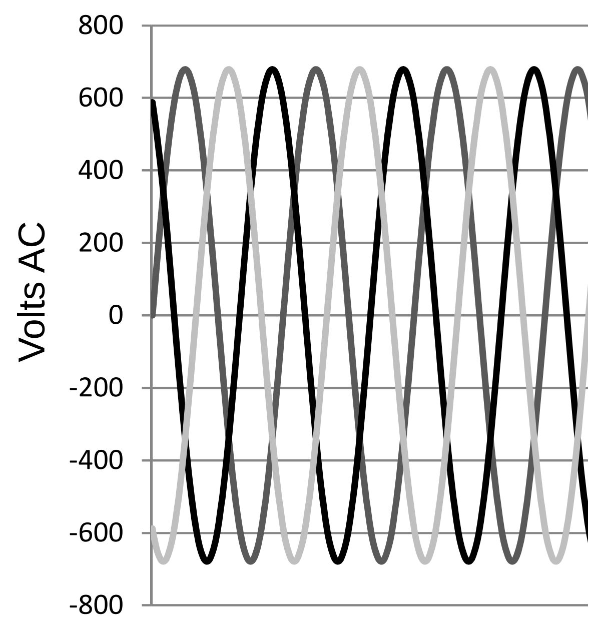
## Single Phase Systems

- Simple topology and control
- Low Power & Voltage
- High DC ripple voltage/current or increased filtering required
- Higher semiconductor current




## Three Phase Systems

- Simple integration to Utility Grid
- Medium to High Power
- Reduced DC Ripple voltage/current
- Lower semiconductor current



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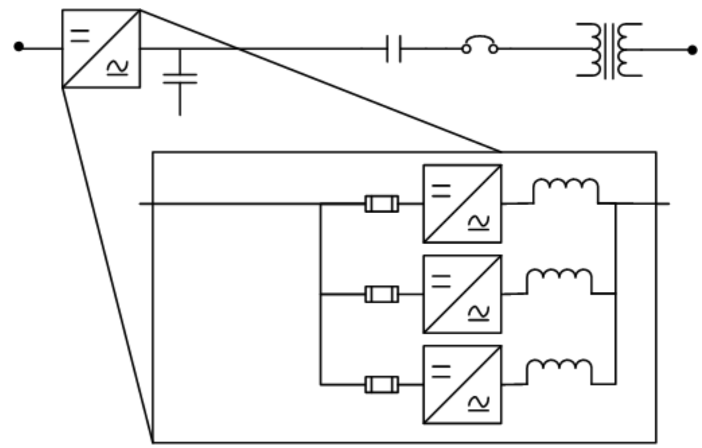
# Transformers for ESS

## Types of Transformers

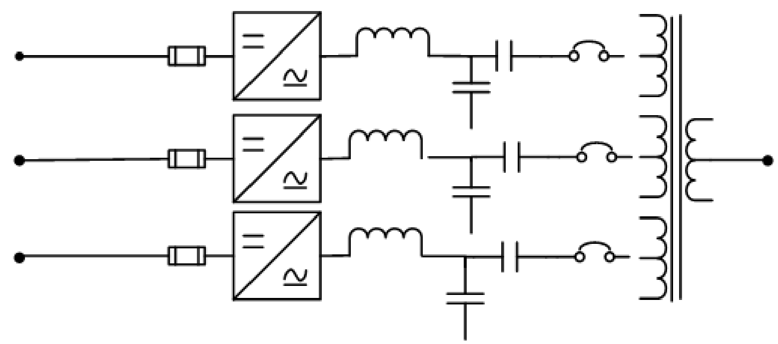
- Vacuum Pressure Impregnated (VPI)
- Oil Immersed
- Cast Coil

## Transformer Configurations

- Single winding



- Multiple LV Windings



# Output Protection and Power Quality Assurance

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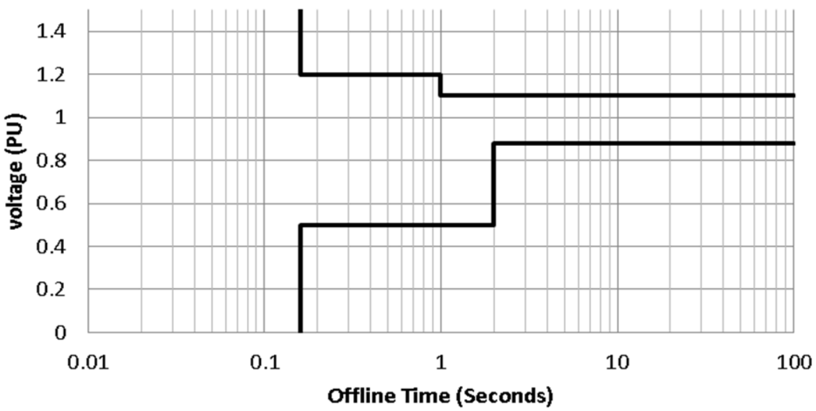
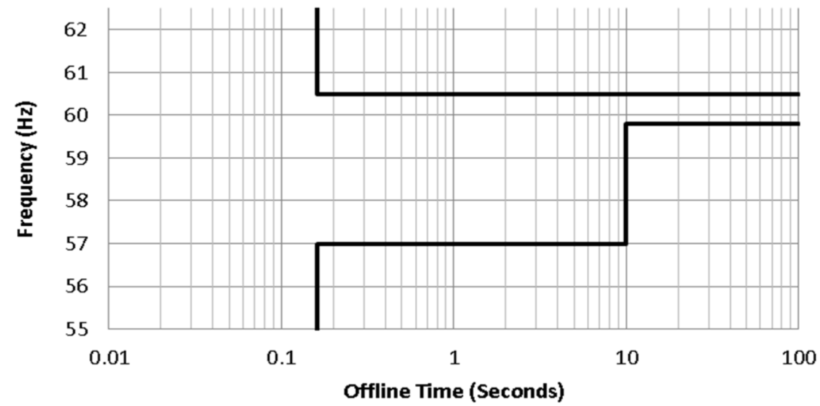
## Voltage and Frequency Protection IEEE 1547




## Output Power Quality

Table 3—Maximum harmonic current distortion in percent of current (I)[a]

| Individual harmonic order h (odd harmonics)[b] | h < 11 | 11 ≤ h < 17 | 17 ≤ h < 23 | 23 ≤ h < 35 | 35 ≤ h | Total demand distortion (TDD) |
|---|---|---|---|---|---|---|
| Percent (%) | 4.0 | 2.0 | 1.5 | 0.6 | 0.3 | 5.0 |

[a] I = the greater of the Local EPS maximum load current integrated demand (15 or 30 minutes) without the DR unit, or the DR unit rated current capacity (transformed to the PCC when a transformer exists between the DR unit and the PCC).

[b] Even harmonics are limited to 25% of the odd harmonic limits above.

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# Conclusions

- Power Conversion is an integral part of Energy Storage Systems
- Limit Conversion Stages to maximize efficiency and minimize complexity
- Integrate systems as soon as practicable to avoid grid interaction and maximize efficiency
- Modularized systems offer unique advantages in redundancy and expandability
- Advanced and hybrid topologies may offer the best solution for specific ESS Challenges

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**Workshop on High Megawatt Electronics:**
**Technology Roadmap Workshop for Increased Power Electronic Grid Applications and Devices**
**May 24, 2012**


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Dynapower Company LLC
South Burlington, VT, USA
www.dynapower.com


Established 1963; Manufacturer of Solid State Power Conversion equipment, Battery Management Systems, VPI, Cast and Oil filled Transformers and DC Power Supplies.

George

Berntsen

FuelCell Energy

National Institute of Standards and Technology
U.S. Department of Commerce

# High MW Power Conditioning Systems Workshop

- Fuel Cell Applications for Power Electronics
- Prospects for Increased Penetration

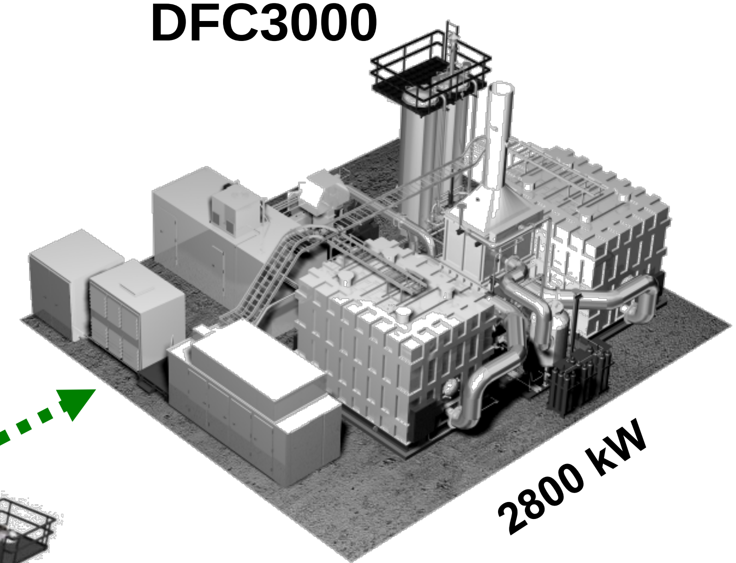
G. Berntsen, 5/24/12

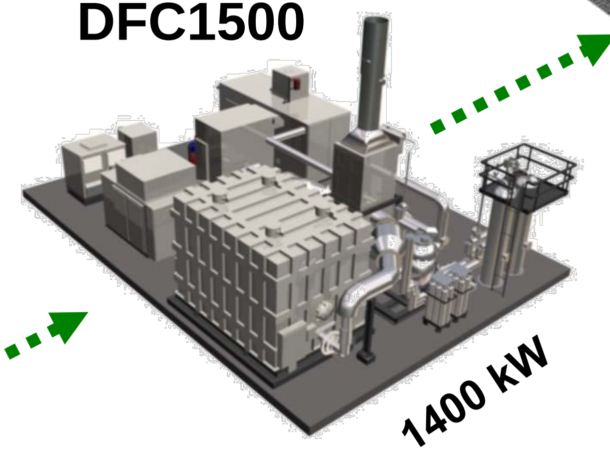
FuelCell Energy

# DFC Models

Direct FuelCell® power plants are generating ultra-clean, efficient and reliable power at more than 50 locations worldwide:

- Over 180 megawatts of power generation capacity installed or in backlog,
- Generated more than one billion kilowatt hours of ultra-clean power.

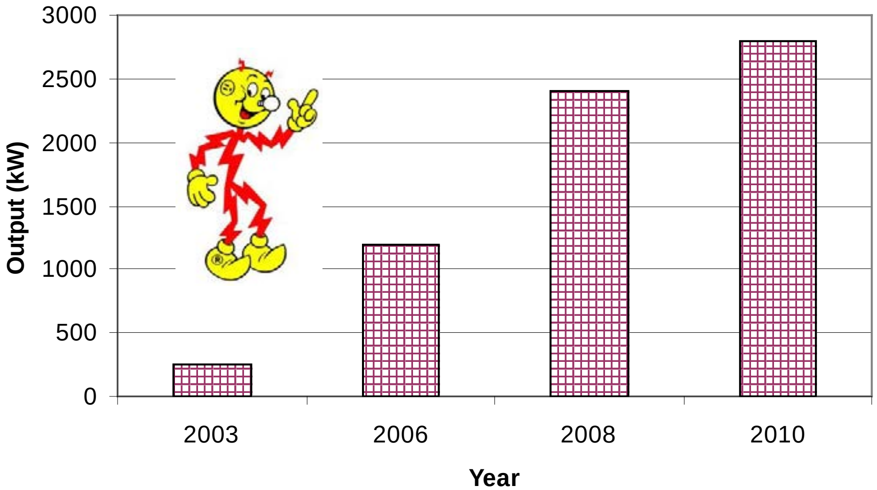


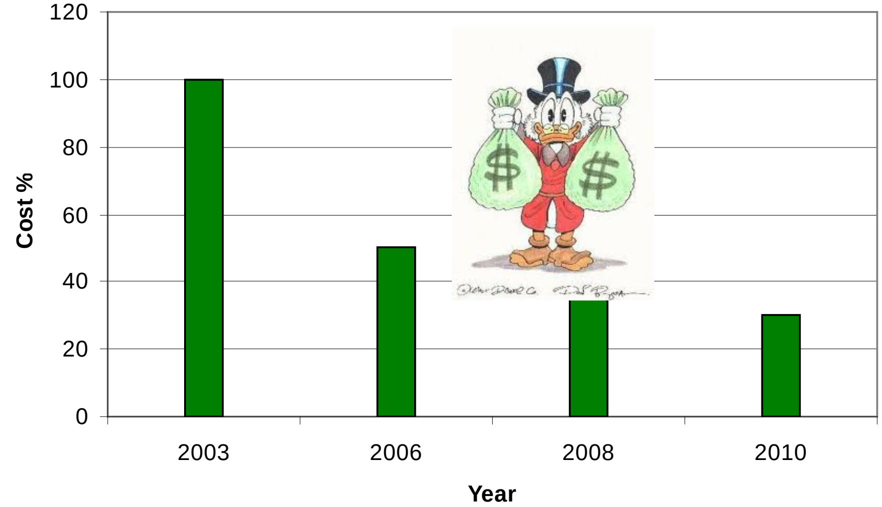

FuelCell Energy

# Scale-Up and Cost Reduction

Rated Power (kW)




Cost ($/kW)



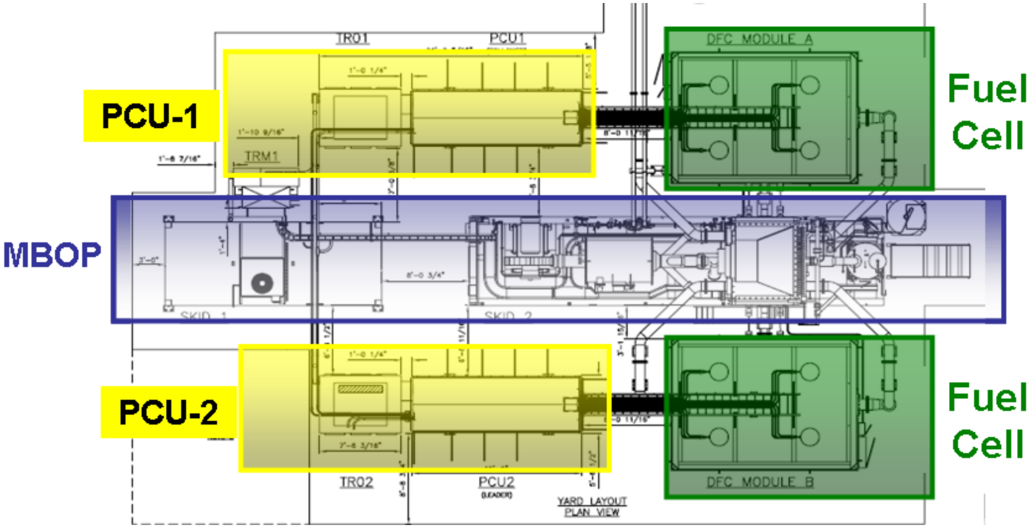

70% $/kW cost reduction achieved through:

- Value Engineering
- Power Up-Rate, Economy of Scale

**Gross Margin Positive Sales**

FuelCell Energy

# 3.0 MW Plant




- ❖ (2) 1500kW Power Trains
  - Common PCU, Module = Volume Savings
- ❖ Economy of Scale Achieved Thru:
  - Common Mechanical Balance-of-Plant (MBOP)
  - Transactional Costs, Service

# Scale-Up Limitations

Fuel Cell Module Size

- Road Transport Constraints

1.4 MWnet module

>100,000 lbs.

Max. Height

Max. Width

FuelCell Energy

# Multi-MW Sites (4 x DFC3000)


**10.4 MW**
Yulchon, S.Korea

**11.2 MW**
Daegu, S.Korea

22.9kV Express Feeder Connection to Sub-Station

FuelCell Energy

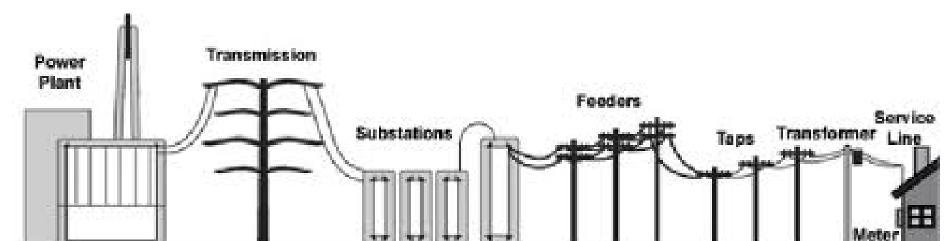
# Scale-Up Limitations

## Distribution System Limitations

- Feeder Capacity (7-12MVA)
  - Express Feeders needed > 1.5/3.0 MW
- Sub-Station Minimum Load
  - Voltage Regulation Limitations
  - Protection Scheme Limitations
- Smart Grid Technologies May Reduce Technical Constraints
  - Jurisdictional, Statutory Constraints.

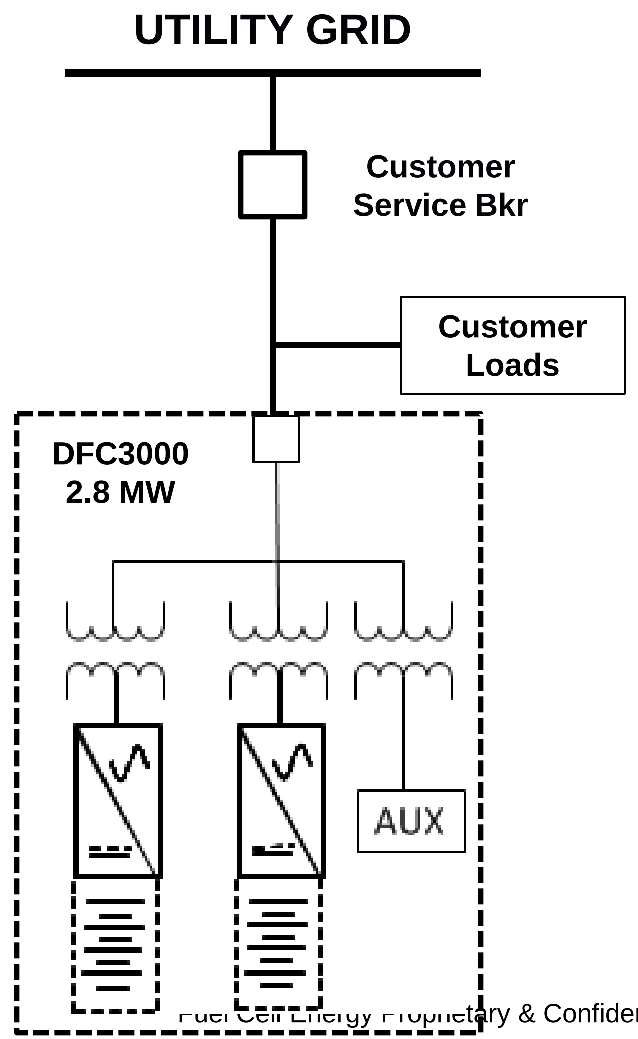
## Transmission System Interconnection

- Requires much larger plant size (50MW) to be cost effective.



**Grid Connected Mode**
Normal Operation

- Baseload, Full Power Production
- >90% Capacity Factor
- Current Control Mode
- Match & Follow Grid Voltage
- UL-1741 Anti-Islanding Detection
  - Abnormal Volt. & Freq.
  - Active anti-islanding algorithm



# DFC Capabilities

## Stand-Alone Mode

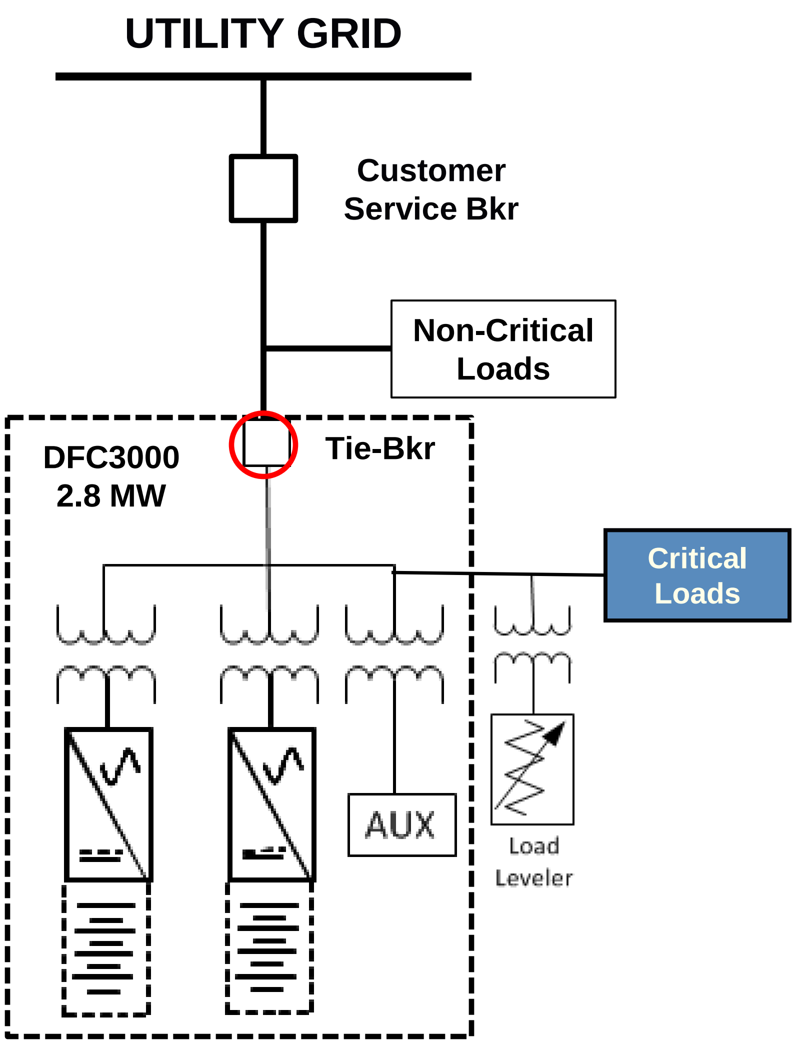
Grid Outage

Upon detection of abnormal Volt./Freq.

- Tie Breaker Opens
- Switch to Voltage Control Mode
- Voltage to Critical loads recovered <4 cycles
- Load Leveler Starts to maintain constant fuel cell load for varying loads.
  - PLC controlled resistive load bank

Challenge: Failed transitions

- e.g. Instantaneous Over-current trip instead of transition on under-voltage.
- Plan to address in LVRT development.

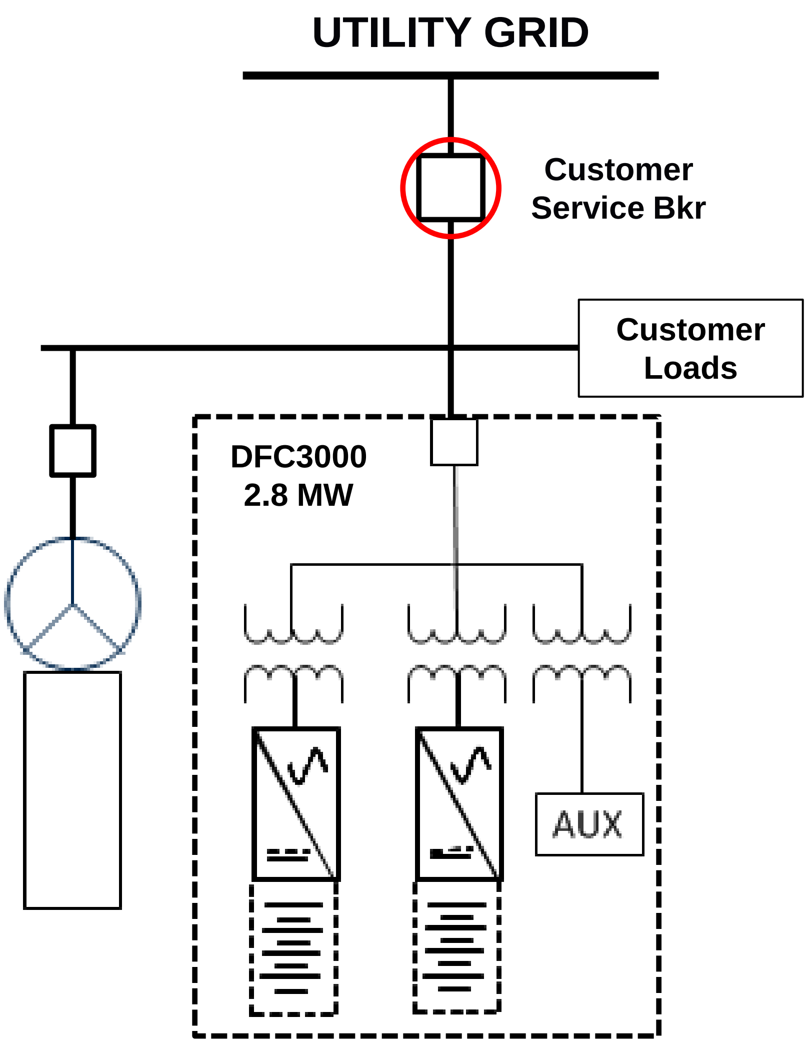


# DFC Capabilities

## Micro-Grid Base Load Mode

Typical Sequence of Operation:

- t0: Grid Outage
- t1: DFC transitions to Stand-Alone Mode, Facility goes dark
- t2: Genset(s) starts, Service Breaker Opens, Sends micro-grid signal to DFC
- t3: Genset connects to bus at rated voltage and frequency.
- t4: DFC syncs with genset and connects to bus with wider V&F relay settings and active anti-islanding disabled.
- t5: DFC ramps to rated power in 5 minutes.



# Micro Grid Experience

## FCE is actively implementing micro-grid mode at several sites.

- Parallel operation with other generators when utility service unavailable
- Customer facilities, behind-the-meter applications
- Interruptible and Seamless Applications

**Recent Micro grid Implementations:**

**Central CT State University**

- Gensets & 1.4MW fuel cell

**San Jose Water Treatment Plant**

- Gensets & 1.4MW fuel cell

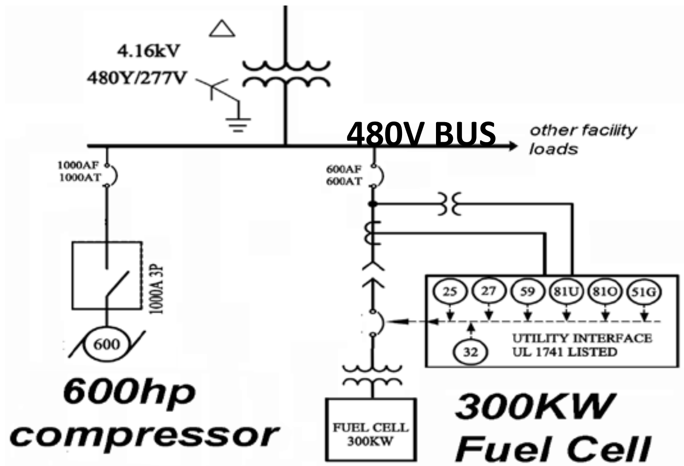
**Santa Rita County Jail**

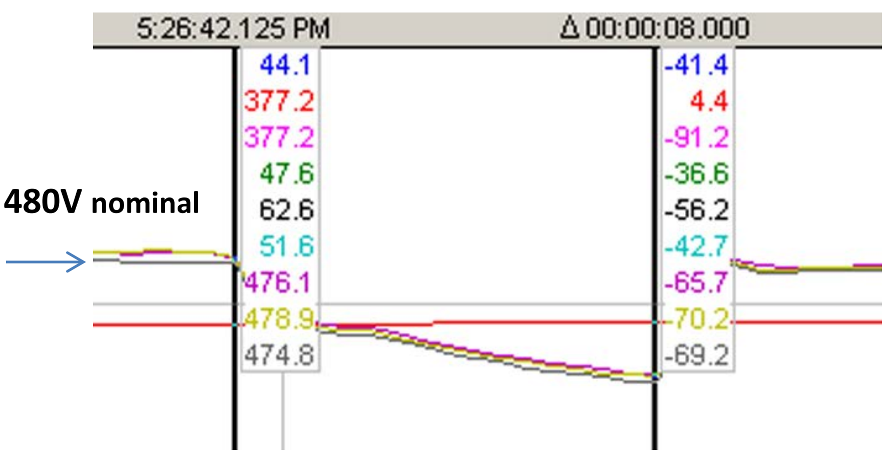
- DOE Smart Grid Demonstration
- Facility Static Switch Disconnect
- 1MW early generation Fuel Cell
- Gensets,1mw solar,
- 2MW energy storage

FuelCell Energy

# Reactive Power Support

## All plants capable of generating rated output from (-) 0.9 to (+)0.9 pf




***Case Study:***

- *A 600hp compressor's start-up pulled bus voltage down below 88% for almost 8 seconds.*
- *The voltage sag was below UL-1741 / IEEE1547 limits requiring the fuel cell to disconnect.*

***Solution:***

- *The controls that start the motor now also provide a signal to the fuel cell to add 130KVAR.*
- *The leading reactive power offsets the compressor start-up and voltage sag is now much less, enabling the fuel cell to stay connected.*

# In Development

**Low Voltage Ride-Through**

- Germany is a New Area of Business Development
- LVRT required for fuel cells connected to the Medium Voltage Network (i.e. Distribution System)

Challenges:

- Technical Approach
- German Certification Agency
- Testing Facility

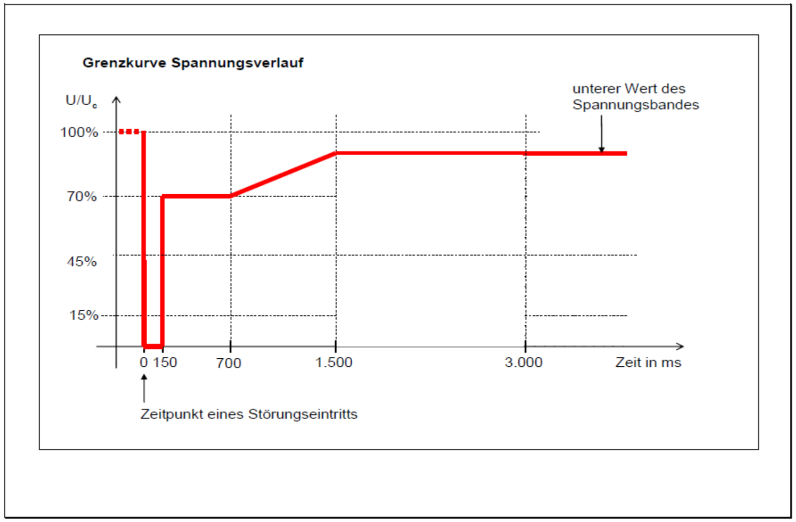



**Figure 2.5.1.2-1: Borderline of the voltage profile at the network connection point of a type-1 generating plant**

# Favorable Trends

**Recent Legislation in Connecticut and California enables utilities to procure Distributed Generation**

- Ensures optimal siting for enhancing Distribution System
  - Power Quality
  - Reliability
  - Load Constraints
- Reduces project uncertainty regarding Electric System upgrade feasibility and costs.

**60MW Projects in process in S. Korea with Utility**

FuelCell Energy

# QUESTIONS?

TJ Singh

UTC Power

A United Technologies Company

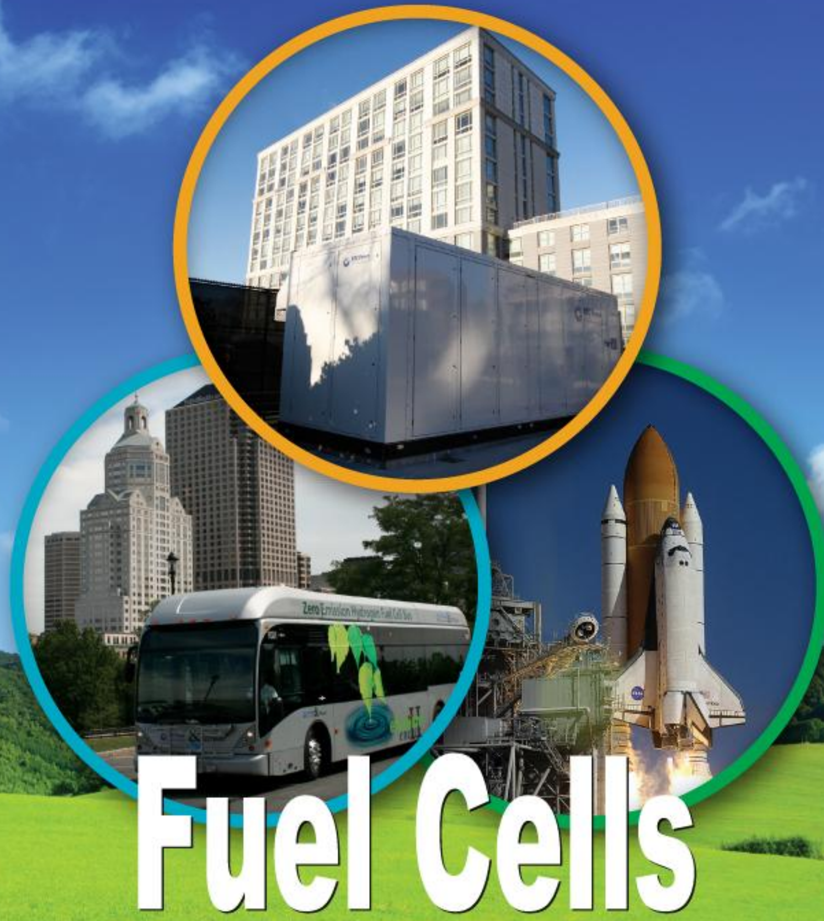
energy

Reinvented

# Fuel Cell Power Electronics – Status & Challenges

Tejinder Singh – Engineering Manager

UTC Power is a world leader in developing and producing fuel cells that generate energy for buildings, transportation and space & defense applications.




Energy Productivity

Energy Security

Energy Responsibility

# Agenda



- UTC Power Overview
- Product Portfolio
- Stationary Applications
- Transportation Applications

# United Technologies Corporation

UTC Power
A United Technologies Company

## Fortune 50 corporation

$58.2B in annual sales in 2011

~60% of sales are in building technologies

Strong energy efficient & distributed energy product portfolio


UTC Power

OTIS

Carrier

Hamilton Sundstrand


PRATT & WHITNEY
DEPENDABLE ENGINES

UTC Fire & Security

## About Us

- Fuel cell technology leader since 1958
- ~ 450 employees
- 768+ active U.S. patents,
  258 additional U.S. patents pending
- Global leader in efficient, reliable, and sustainable fuel cell solutions

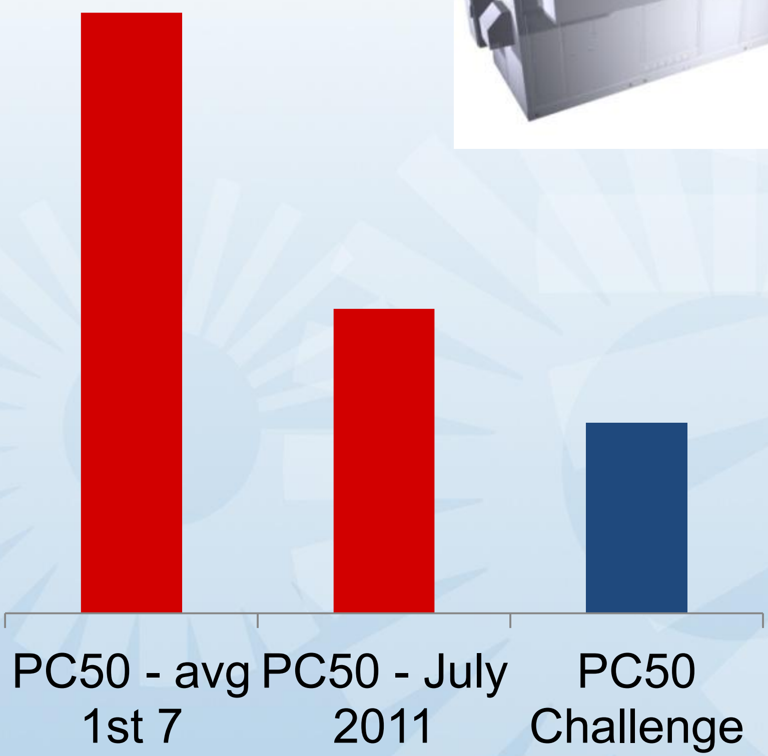
### Stationary Fuel Cells

### Transportation

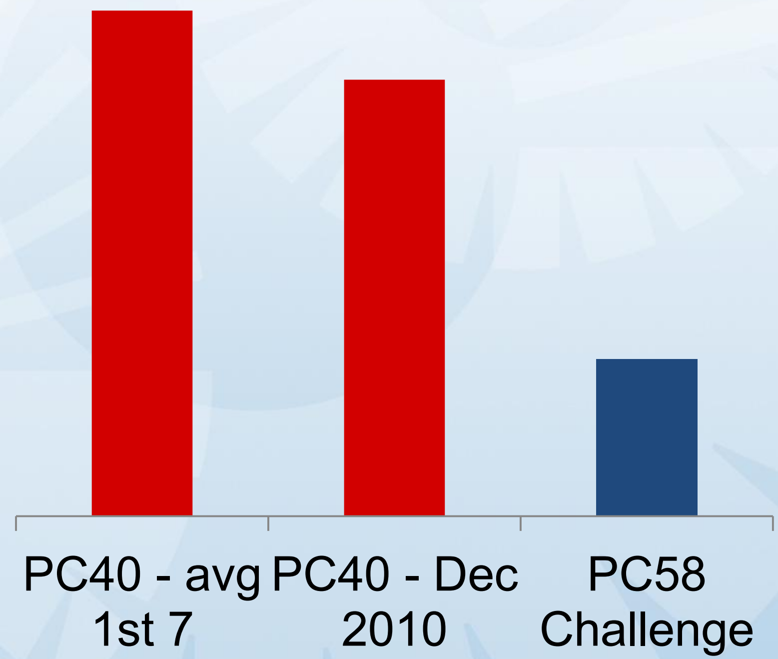

### Space & Defense

# Grand Challenge : Cost

## Stationary




## Transportation



# PureCell® Model 400 System

UTC Power
A United Technologies Company

## Key Features


[1] 1st year average
[2] ~ 450 kW
[3] Through use of multiple Model 400 systems
[4] California Air Resources Board 2007 emissions standard

### Output and Efficiency

- 400 kW net electric output
- 42% electrical efficiency[1]
- 1.5 MMBtu/hr heat output[1 2]
- Up to 90% system efficiency

### Design Characteristics

- 10-year stack life
- Grid-independent capability
- Load following capability
- Natural gas fuel source
- Multi-megawatt capable[3]
- Certified to FC-1, UL, CARB 2007[4]

# PureCell® Model 400 System

UTC Power
A United Technologies Company

## Process Overview

**1 Fuel Processor**

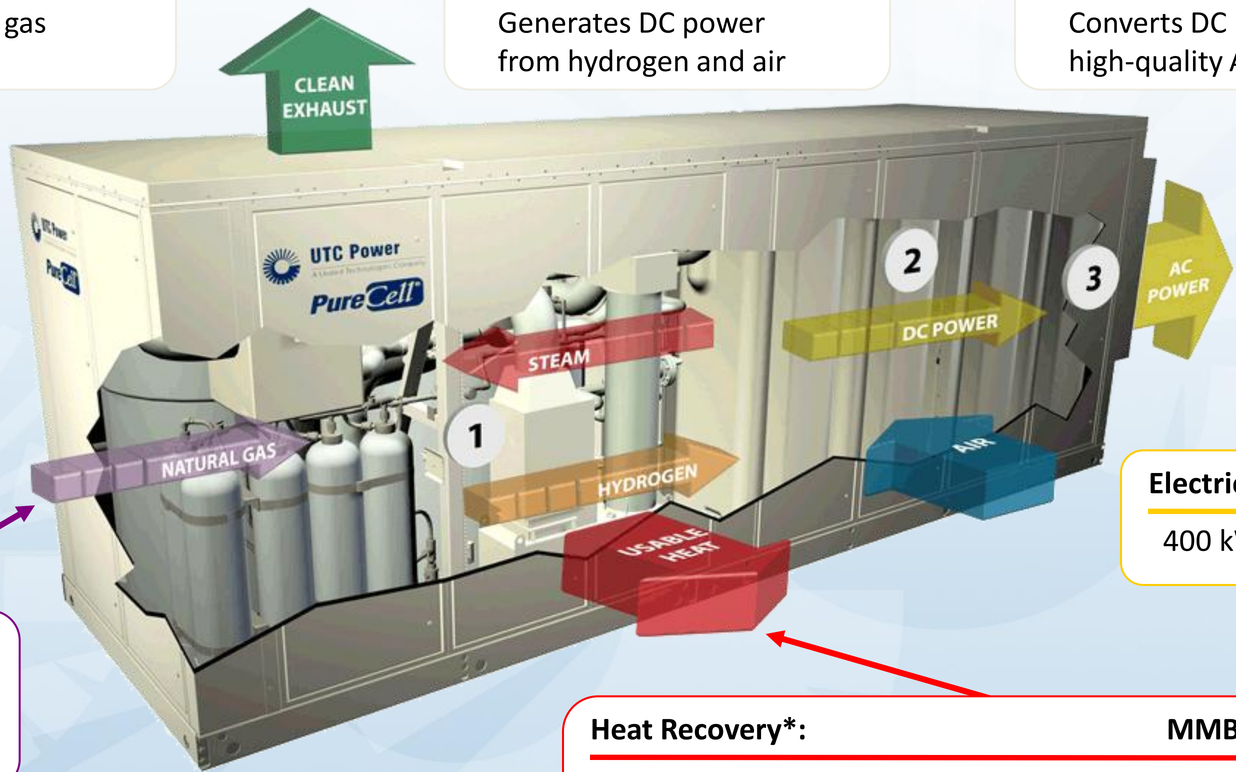
Converts natural gas fuel to hydrogen

**2 Fuel Cell Stack**

Generates DC power from hydrogen and air

**3 Power Conditioner**

Converts DC power to high-quality AC power




**Electric Output:**

400 kW, 480V, 60 Hz

**Fuel Input* (LHV):**

Natural gas
3.79 MMBtu/hr

| **Heat Recovery*:** | **MMBtu/hr** |
|---|---|
| **High-Grade** up to 250°F (120°C) | 0.717 |
| **Low-Grade** up to 140°F (60°C) | 1.017 |

* Beginning-of-life values

# PureCell® Fleet



## Model 200

- 270+ systems installed across 19 countries on 6 continents
- 9.7+ million hours of field operation
- More than 1.6 billion kWh of electricity generation
- Average availability 2008 – present: **96%**
- Demonstrated 10 year cell stack life (design life of 5 years)
- Fleet Leader – Casino in Uncasville, CT with 85,181 hrs or 15,609 MWHRS


## Model 400

- In production since 2010
- 42 systems in commercial operation
- Over 410,000 hours of field operation
- More than 150 million kWh of electricity generation
- 2011 Fleet availability: > **96%**
- 10-year stack design life
- Delighted customers placing additional orders

SAMSUNG Coca-Cola COX COMMUNICATIONS
New York Power Authority Price Chopper WHOLE FOODS MARKET
Stop&Shop SUPERVALU

# PureCell® Model 400 Solution

UTC Power
A United Technologies Company

## Flexible Fuel Cell Application and Varied Experience

Price Chopper
New York


St. Helena Hospital
California

The Octagon
New York


Coca-Cola Enterprises
New York

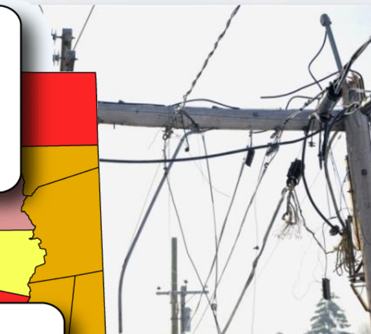
Samsung/GS Power
South Korea

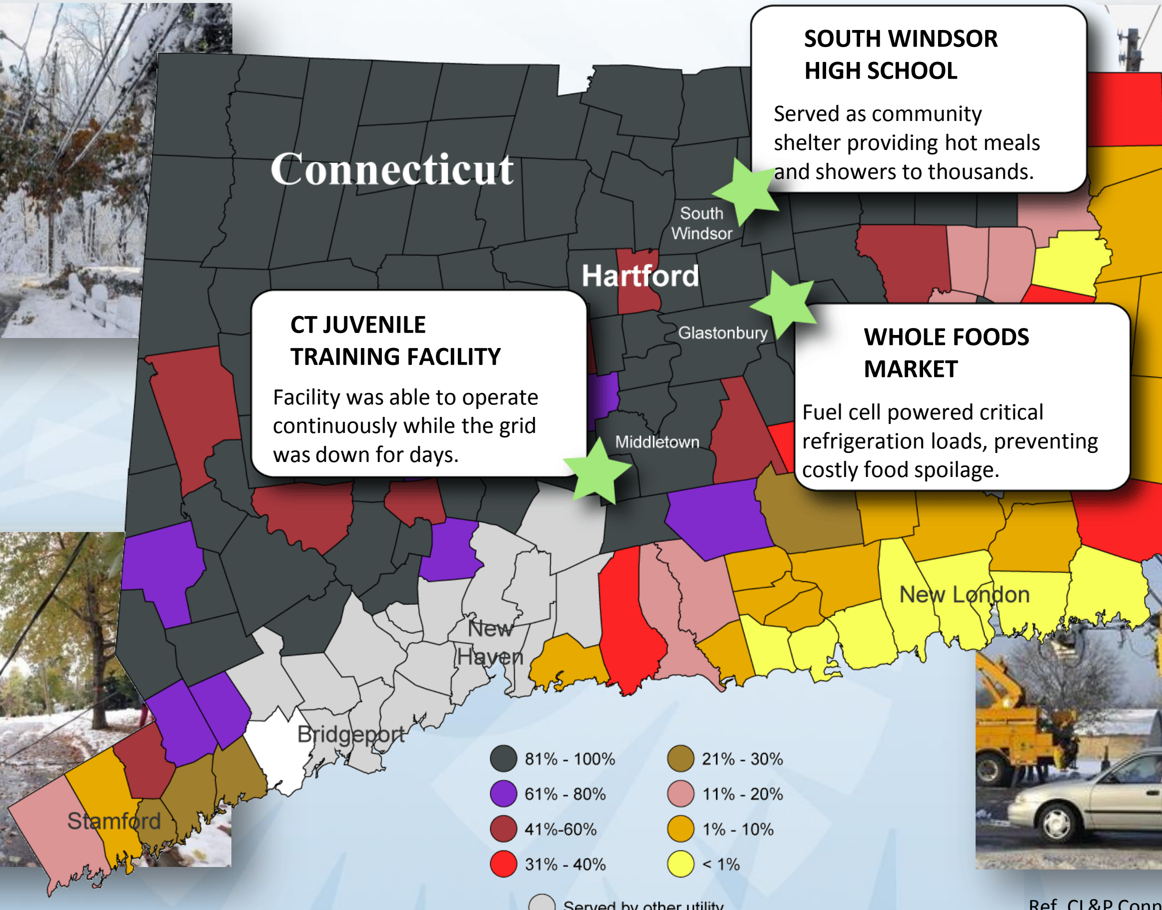
World Trade Center (Freedom Tower)
New York

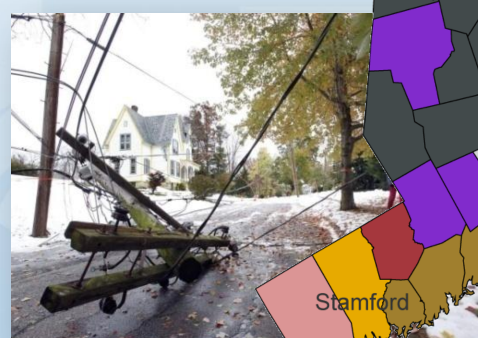
# Fuel Cells: Power Through the Storm

UTC Power
A United Technologies Company

**PureCell® systems keep CT businesses and shelters running through prolonged power outages resulting from the October 2011 winter storm.**





Ref. CL&P Connecticut Outage Map for October 2011

# Supermarket Open During Blackout

UTC Power
A United Technologies Company

## Reliable Power During Grid Outages (San Diego Albertsons)

- Albertsons supermarket operates throughout September 2011 San Diego power outage
- Was one of the only retail stores in the valley operating during the crisis
- Despite the sweltering heat outside, Albertson's perishable inventory protected thanks to the continued operation of their fuel cell

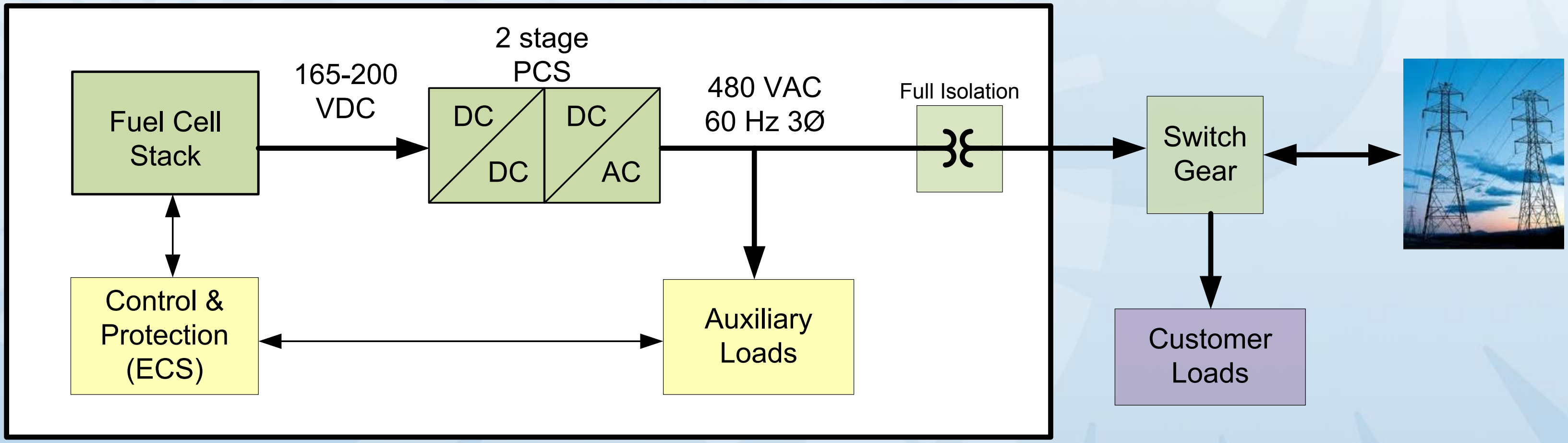

***"When you drive down the neighborhood and the only thing lit is Albertsons, it attracts people,"***

*-Rick Crandall, Director of Sustainability, SuperValu Inc.*


# Evolution from PC25 to PC50

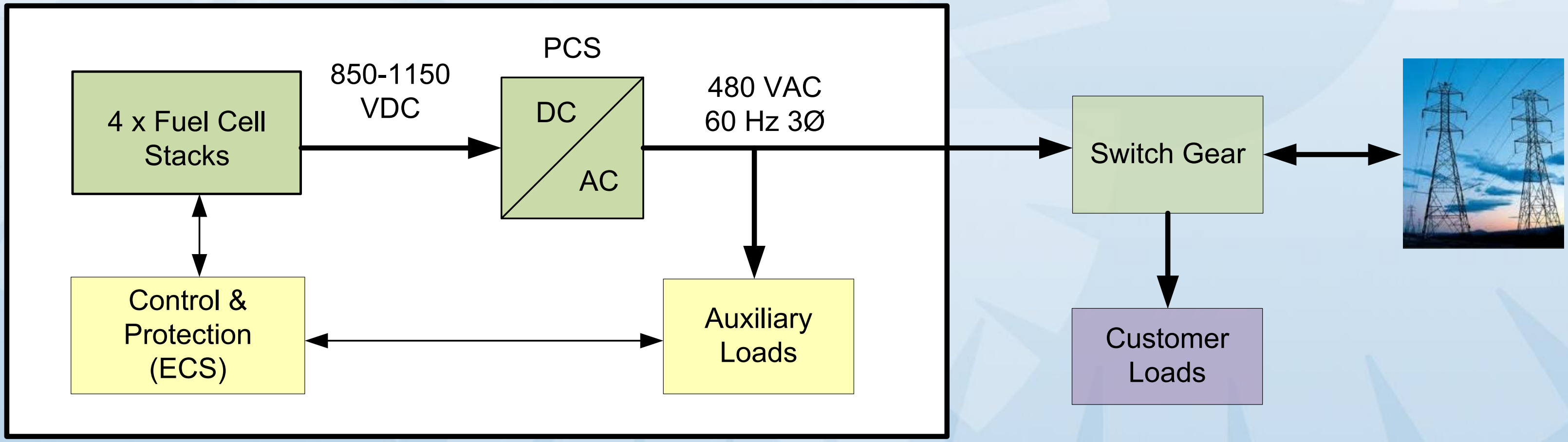


- **PC25**
  - Single Cell Stack Assembly – grounded
  - 2 stage 200kW converter
    - DC/DC converter to boost voltage
    - 3 phase grid connected Inverter
  - Full Isolation transformer for grid connection
    - Capable of Grid Independent Operation
  - PCS is ~93% efficient

# Evolution from PC25 to PC50

- **PC50**
  - Four Cell Stack Assemblies in series to achieve >850V @ base load
  - 400kW / 470kVA inverter
  - Directly connected to grid
    - No isolation transformer
    - Capable of Grid Independent
      - Interruption during transition
  - PCS is ~97% efficient

# Next steps

UTC Power
A United Technologies Company

- Flexible architecture
- Core module system leveraging COTS PCS
- Multiple Unit Load Sharing (MULS)
- Seamless GC/GI transitions
- Microgrid Integration & Secure Communication

# Transportation

*Electrical drive train with FC as a primary source of propulsion power*

## World class performance

- Primary propulsion is UTC's Puremotion™ 120kW proton exchange membrane (PEM) fuel cell
- Fleet experience of more than 600,000 miles
- Fleet leader at a record 12,000 hours and counting
- Additional fleet buses demonstrating similar durability – 7,200 hours
- 18 quiet, zero-emission fuel cell buses are currently in service in the United States
- 2010 and 2011 fuel cell availability is greater than 95% surpassing 85% for conventional engines
- >2x more efficient than diesel powered bus

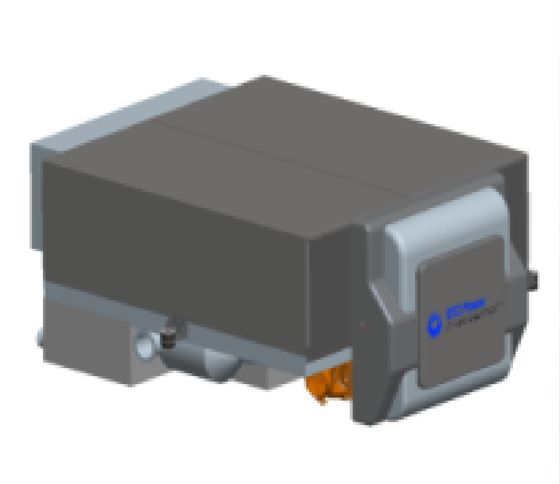
# Transportation

UTC Power
A United Technologies Company

- UTC Power content on PC40 includes:
  - Fuel cell assembly
  - Balance of plant
    - sensors, actuators, blowers, pumps, etc
  - Digital electronic controller
    - Protection
    - Control of cell stacks
    - Communication with external systems
- Utilizes modular inductor, dc dc converter and inverter modules
  - Integrated by bus manufacturer

# Transportation Challenges

- PC58 in Conceptual Design phase
- PC40 vs PC58
  - Cost reduction
  - Reduced envelope
  - Increased power
    - 120kW -> 150kW



- Opportunities for improved integration with external systems
  - Battery management and Optimization
  - Power system flexibility to accommodate different cell stack configurations
  - Use of ultra capacitors for load transients

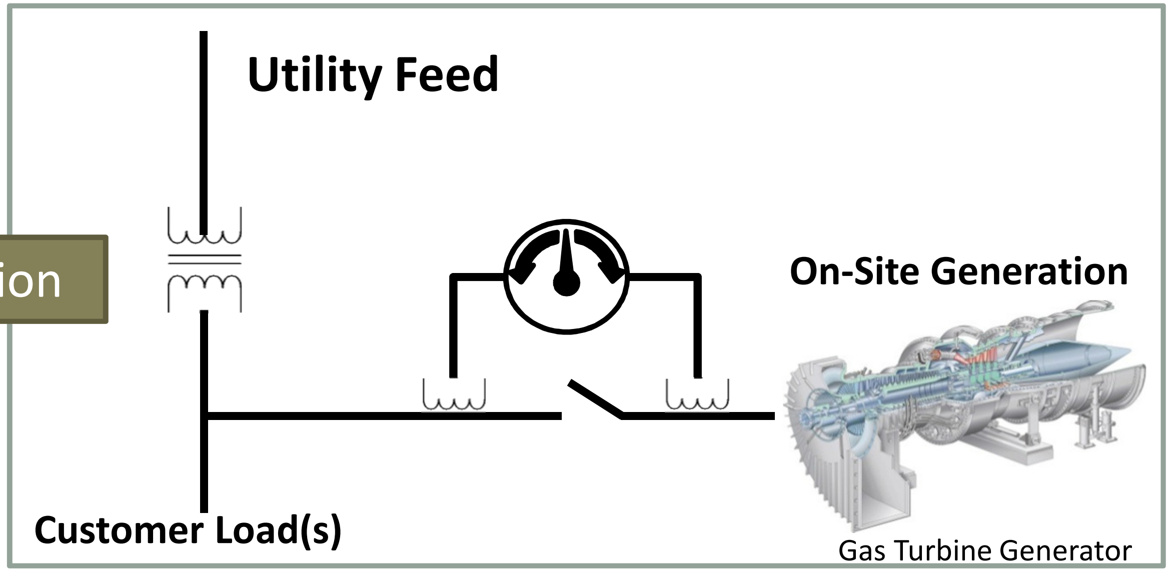
- Questions / Discussion

Shalom

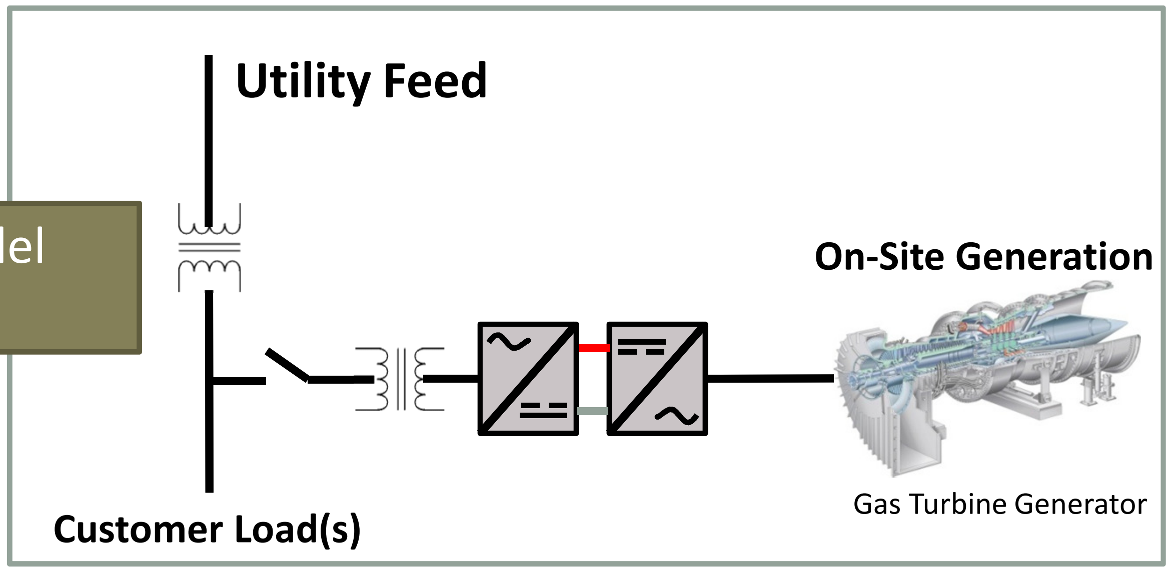
Flank

# Existing Interconnection Approaches

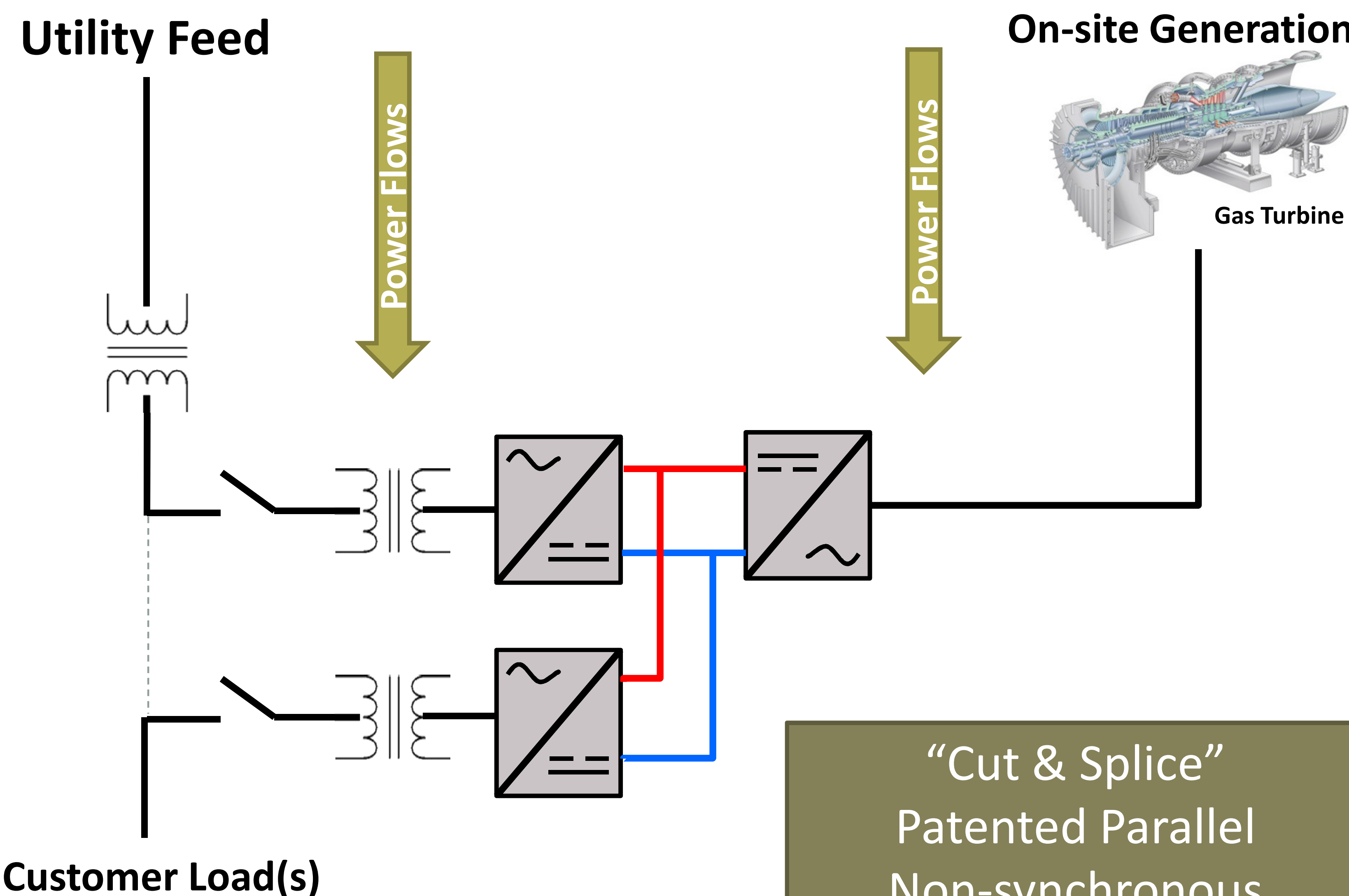
Synchronous Interconnection




Non-synchronous Parallel Interconnection

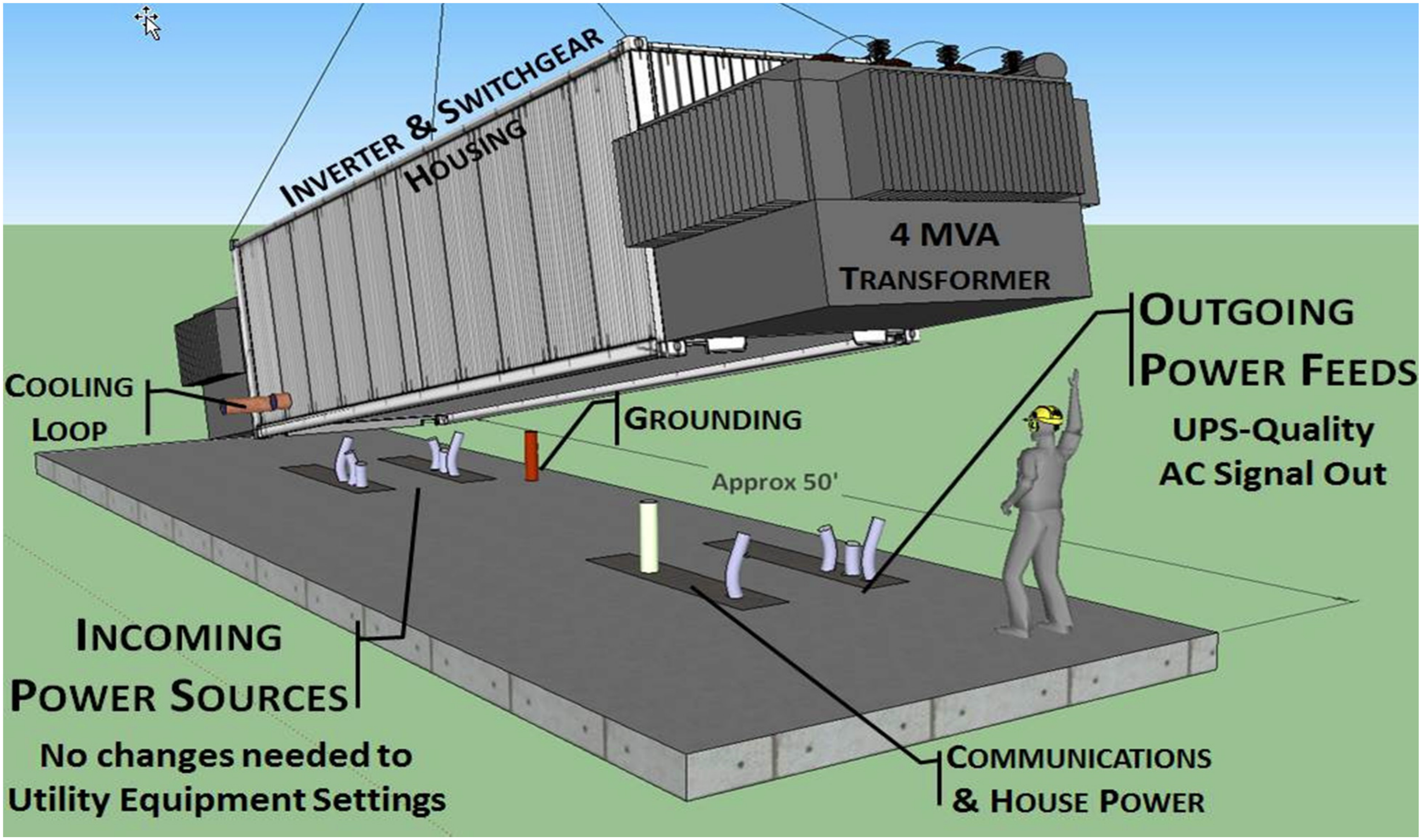


# GridLink$^{TM}$ Interconnection




"Cut & Splice"
Patented Parallel
Non-synchronous
Interconnection

# Packaged Solution: Drop-in, Plug-and-play functionality



# With GridLink the Utility does not see the Microgrid as Generation

**11/08** — Matthew Brown, URS Washington Group:
GridLink will "preclude any potential detrimental effects on the power delivery system [and] eliminate the potential of voltage, frequency, and phase-angle mismatching between the facilities and the utility grid."

**2/09** — Connecticut Light & Power:
"the proposed generator will not have an impact on the CL&P distribution system."

**5/11** — Edison Electric Institute:
"…cutting-edge GridLink technology enables a safe connection between a microgrid and a traditional grid"

**6/11** — Pepco:
" The proposed generators will not operate in parallel with the Pepco electric distribution system."

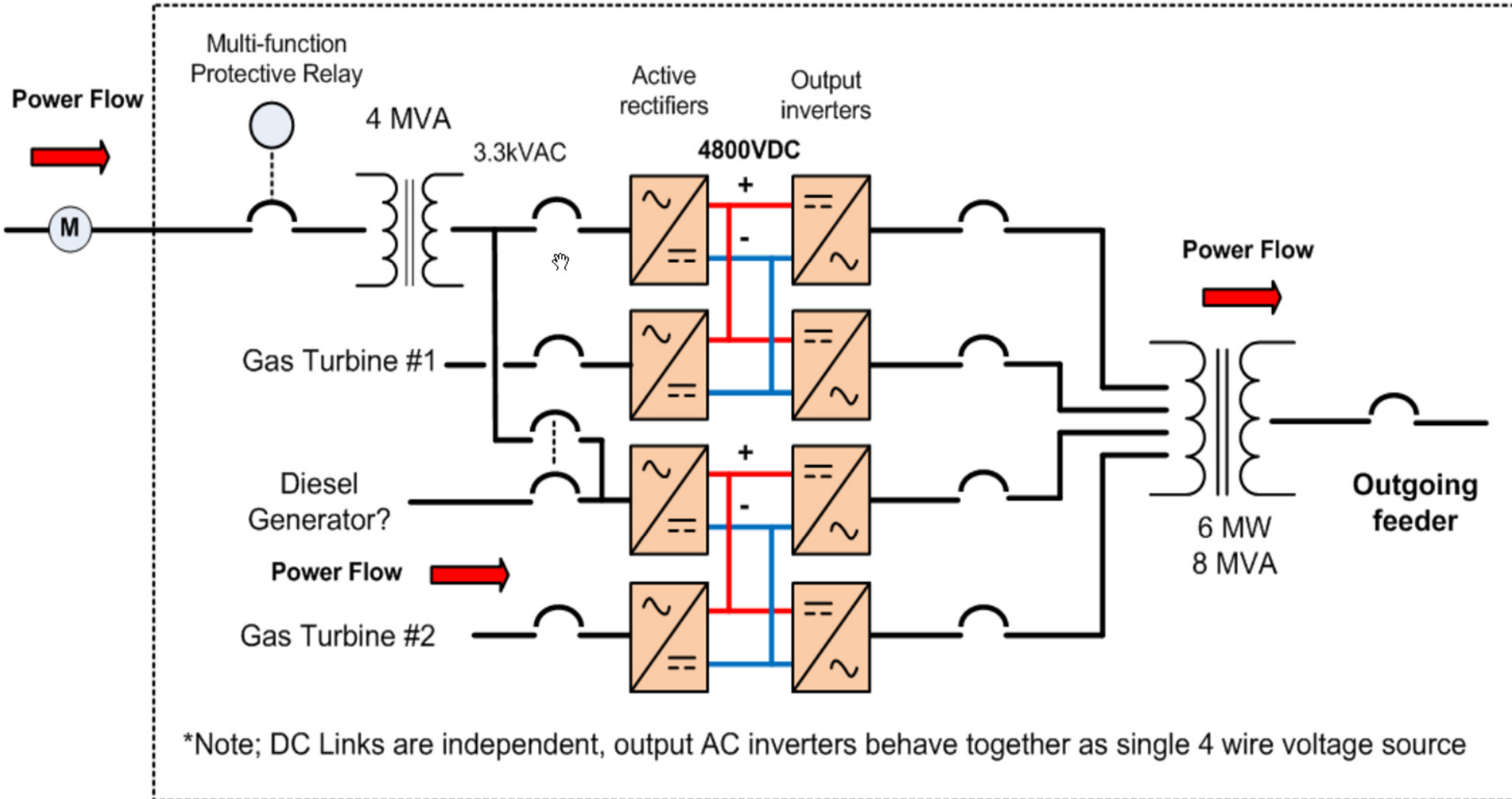
**8/11** — Silicon Valley Power, City of Santa Clara:
" Master Interconnection Agreement"
- One application for microgrid, covers all future generation.

**12/11** — conEdison:
No interconnection application
Microgrid looks like a load to the Utility grid

BGE:
Meeting with **David Eakin** to discuss GridLink for projects in BG&E service territory

PARETO ENERGY

# GridLink: Inside the Black Box





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Duschan
Boroyevich

*Center for Power Electronics Systems*
The Bradley Department of Electrical and Computer Engineering
College of Engineering
Virginia Tech, Blacksburg, Virginia, USA

# Advanced High-Megawatt Converters for New Grid Architectures

***Dushan Boroyevich***

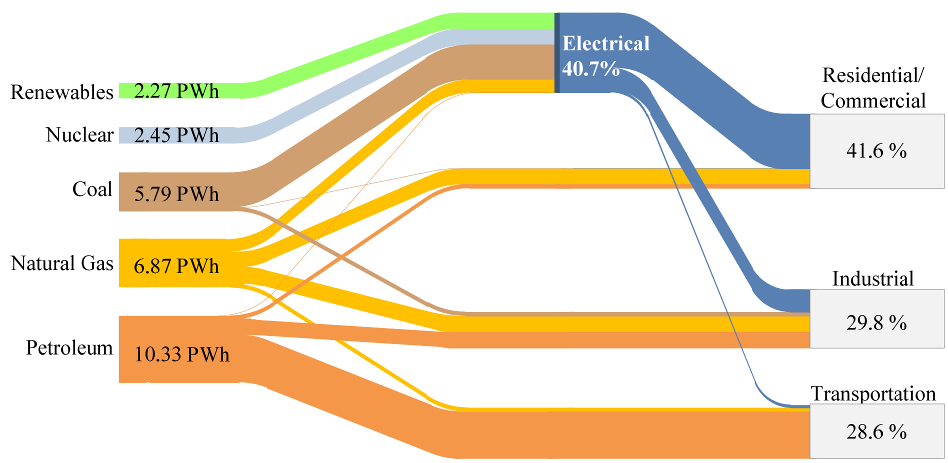
***Presentation at***
**High Megawatt Power Conditioning System Workshop**

**Technology Roadmap**
**for Increased Power Electronic Grid Applications and Devices**

**NIST**
**Gaithersburg, Maryland**

**2012.05.24**

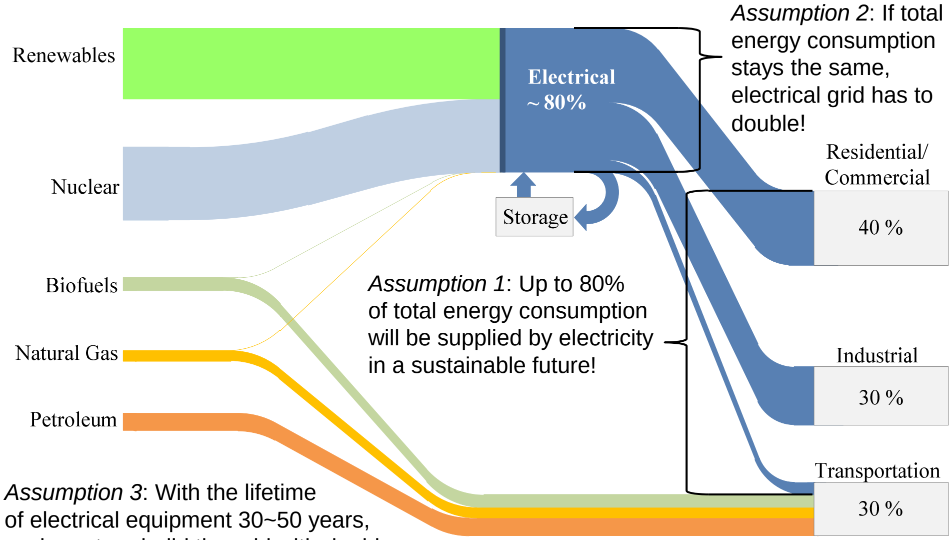
## US Total Energy Flow




Adapted from U.S. Energy Information Administration / Annual Energy Review 2009

CPES 2012.05.24 db-1

## US Energy Flow in Sustainable Future?

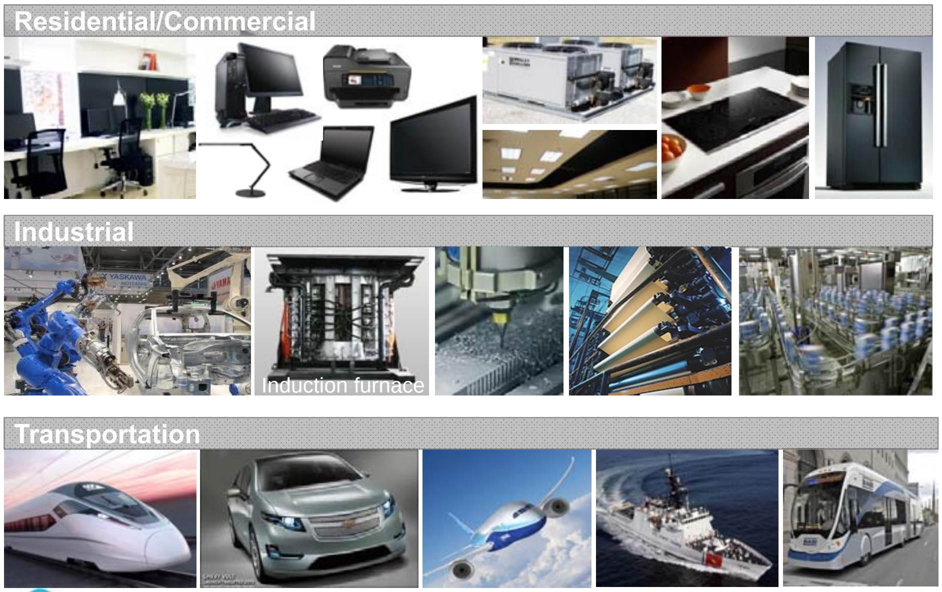



*Assumption 3*: With the lifetime of electrical equipment 30~50 years, we have to rebuild the grid with double capacity in the next 20-30 years!

***How should we do it***

CPES 2012.05.24 db-2

## Most of Electricity is Consumed by Electronic Loads




CPES 2012.05.24

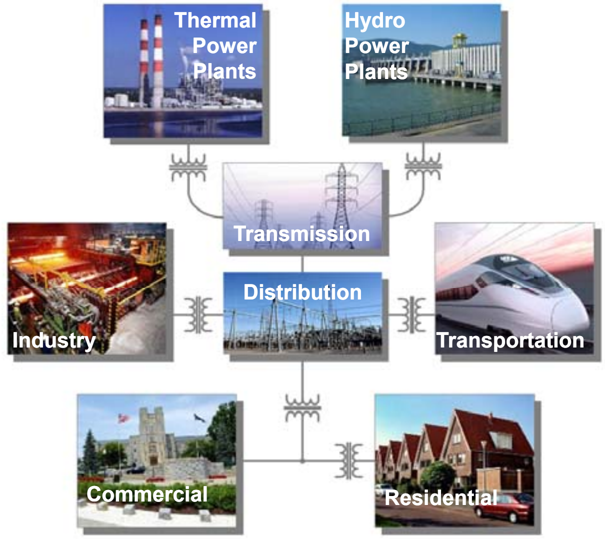
**Electronic loads are constant-power loads.**

db-3

## More Electricity is Supplied by Electronic Sources


CPES 2012.05.24 db-4

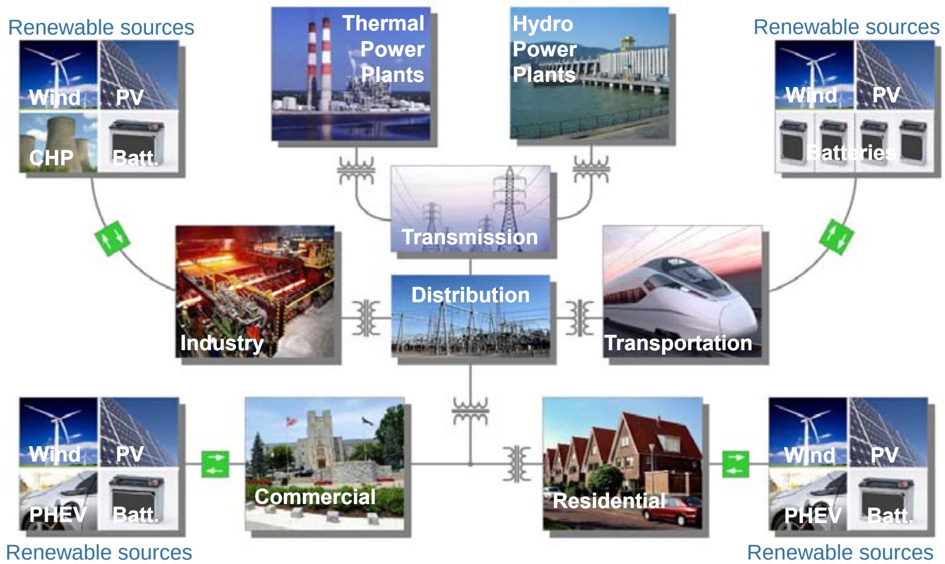
## $20^{th}$ Century Grid



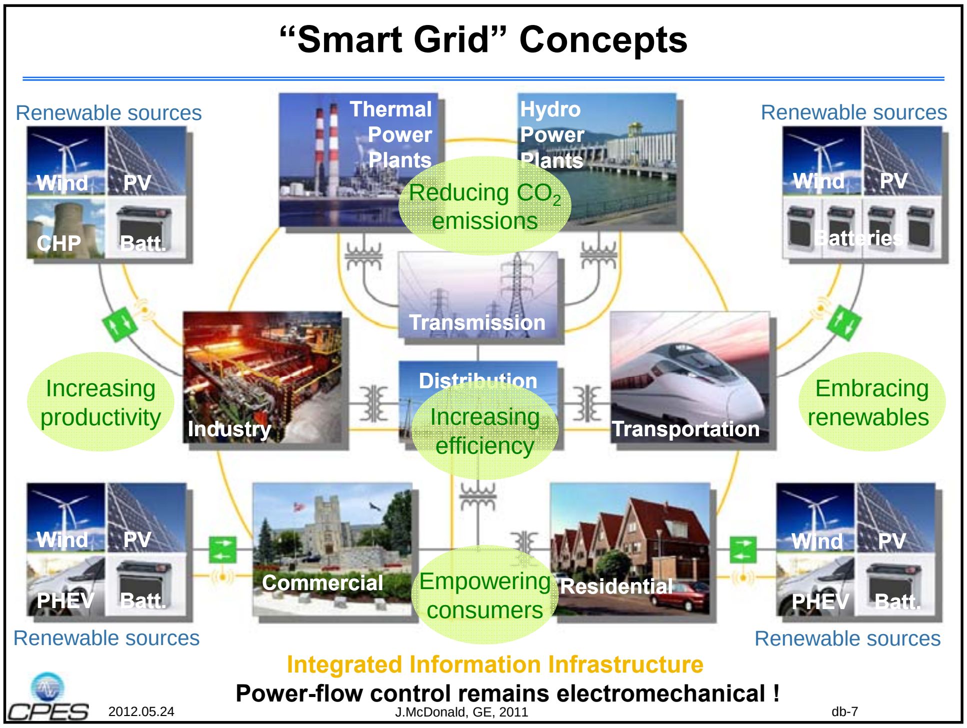

Generation (Centralized)
Transmission (Mesh)
Distribution (Radial Network)

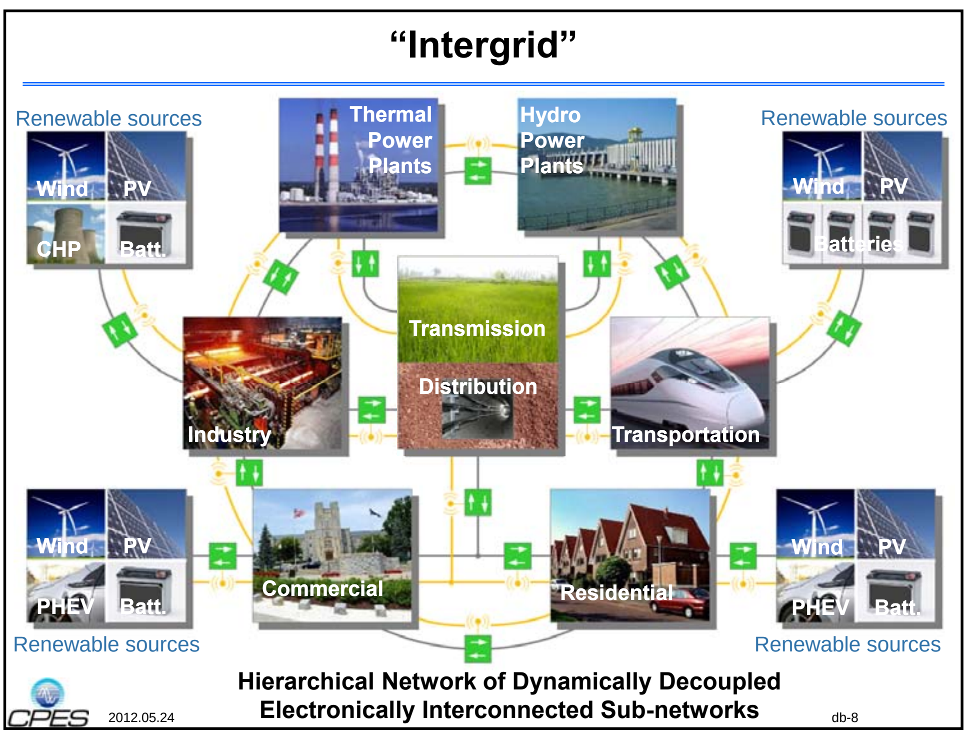
CPES 2012.05.24 db-5

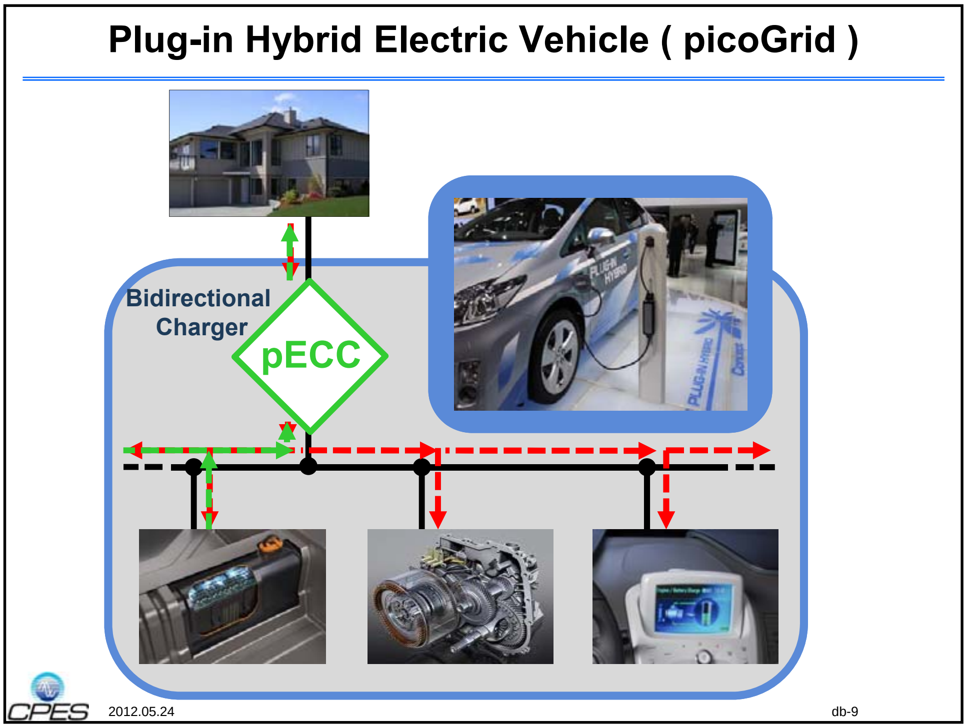
## $21^{st}$ Century Grid?

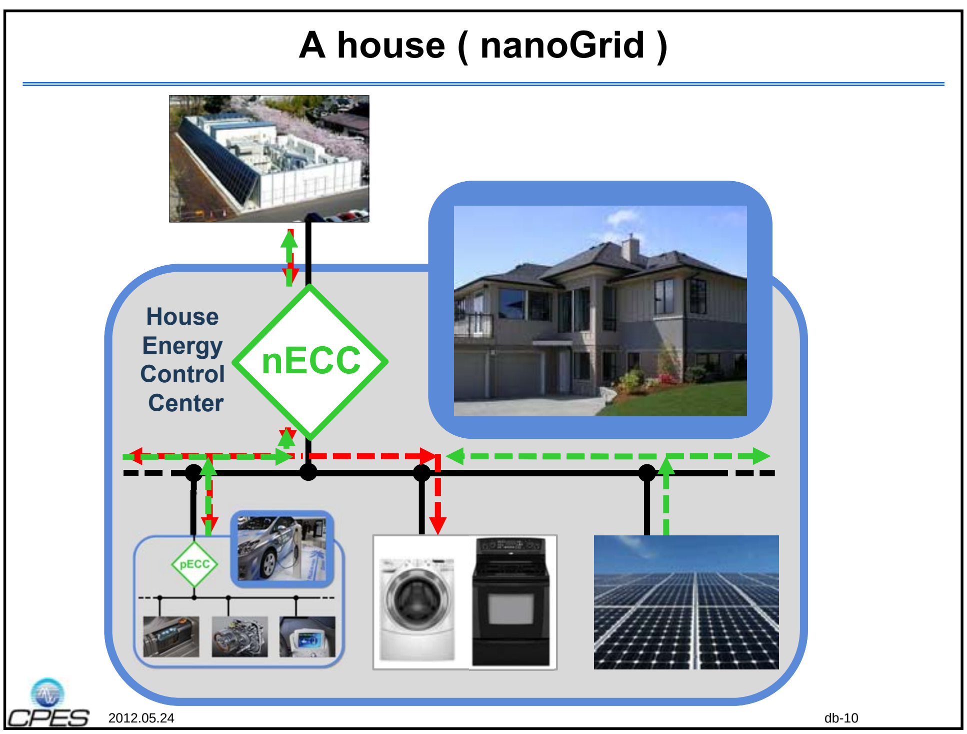



CPES 2012.05.24 db-6


"Smart Grid" Concepts
Renewable sources
Wind
PV
CHP
Batt.
Thermal Power Plants
Hydro Power Plants
Reducing $CO_2$ emissions
Renewable sources
Wind
PV
Batteries
Transmission
Distribution
Industry
Transportation
Increasing productivity
Increasing efficiency
Embracing renewables
Wind
PV
PHEV
Batt.
Commercial
Residential
Empowering consumers
Wind
PV
PHEV
Batt.
Renewable sources
Renewable sources
Integrated Information Infrastructure
Power-flow control remains electromechanical !
CPES
2012.05.24
J.McDonald, GE, 2011
db-7


"Intergrid"
Renewable sources
Wind
PV
CHP
Batt.
Thermal Power Plants
Hydro Power Plants
Renewable sources
Wind
PV
Batteries
Transmission
Distribution
Industry
Transportation
Wind
PV
PHEV
Batt.
Commercial
Residential
Wind
PV
PHEV
Batt.
Renewable sources
Renewable sources
Hierarchical Network of Dynamically Decoupled
Electronically Interconnected Sub-networks
CPES
2012.05.24
db-8

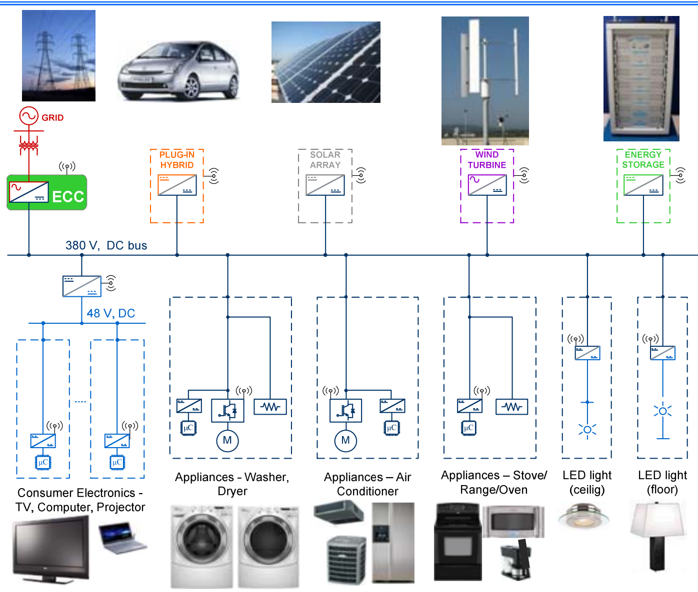

Plug-in Hybrid Electric Vehicle ( picoGrid )
Bidirectional Charger
pECC
CPES
2012.05.24
db-9


A house ( nanoGrid )
House Energy Control Center
nECC
pECC
CPES
2012.05.24
db-10

## Home DC nano-Grid Experiment at CPES

**Nanogrid* with the bus architecture**

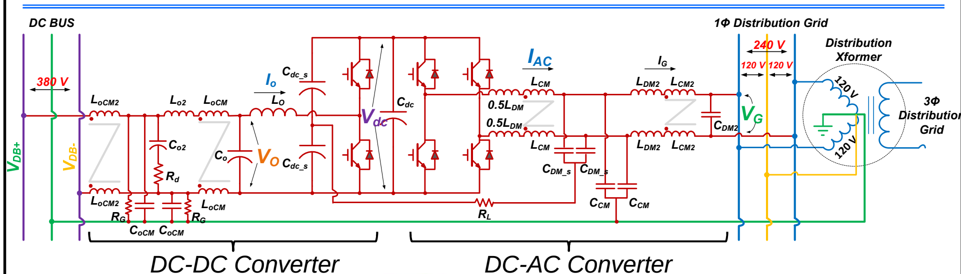
- Two voltages
- Wireless communication



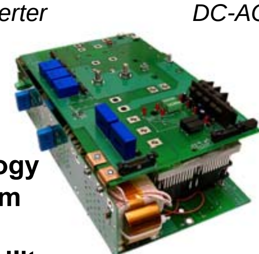

- Bidirectional power conversion
- Separation of dynamics
- Integrated protection
- Load management
- DG management
- Data acquisition
- Communication
- Islanded operation

CPES 2012.05.24 * J. Bryan, R. Duke, S. Round, 2003 db-11

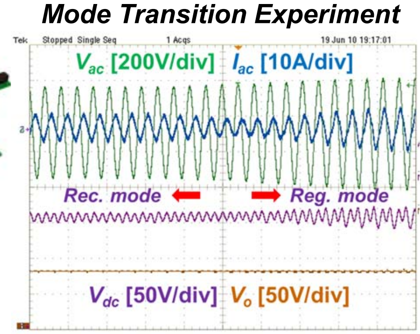
## Single-phase nano - Energy Control Center




***10 kW, 20 kHz CPES Prototype***



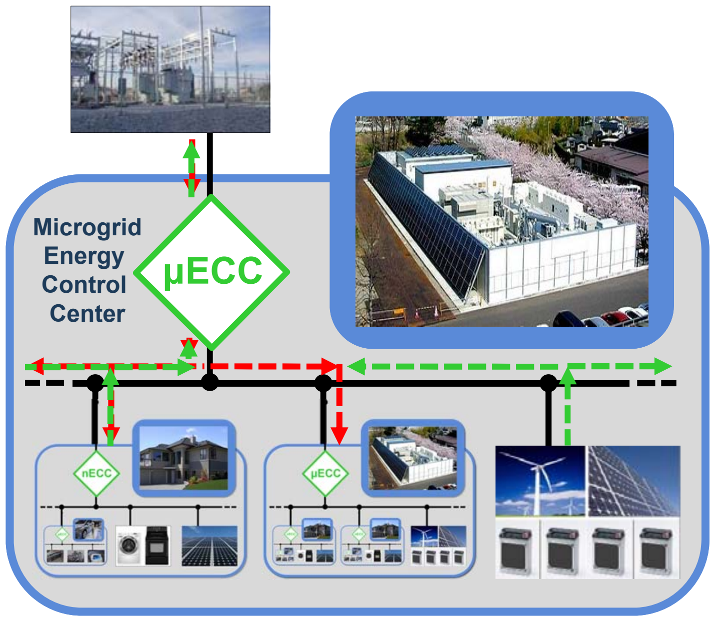
***Mode Transition Experiment***




- **Bi-directional topology**
- **Bi-dir. control system**
- **Bi-dir. current limit**
- **Bi-dir. EMI compatibility**
- **Low dc leakage current**
- **Low cost, high density**

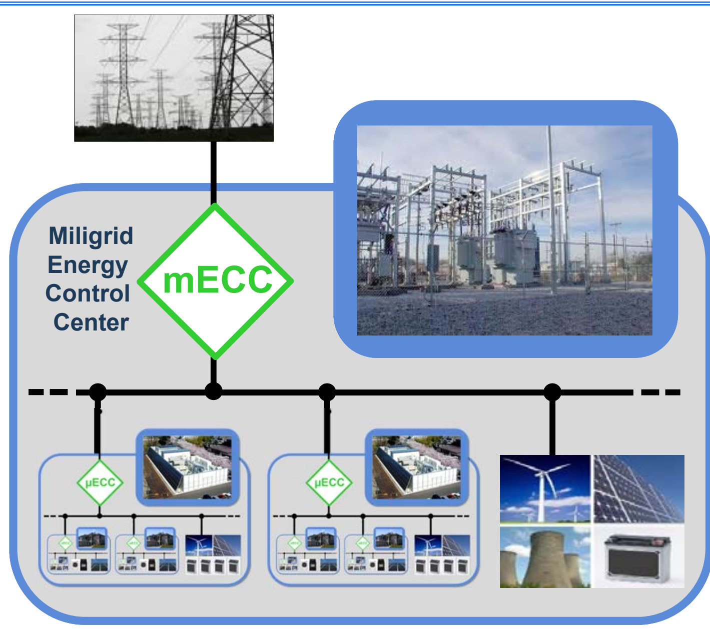
CPES 2012.05.24 db-12

# Microgrid




CPES 2012.05.24 db-13

# Miligrid

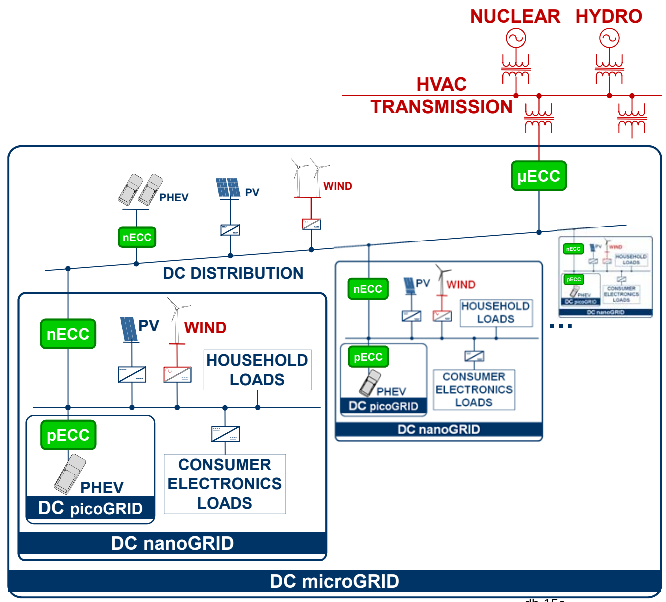



CPES 2012.05.24 db-14

## ¿ Intergrid ?

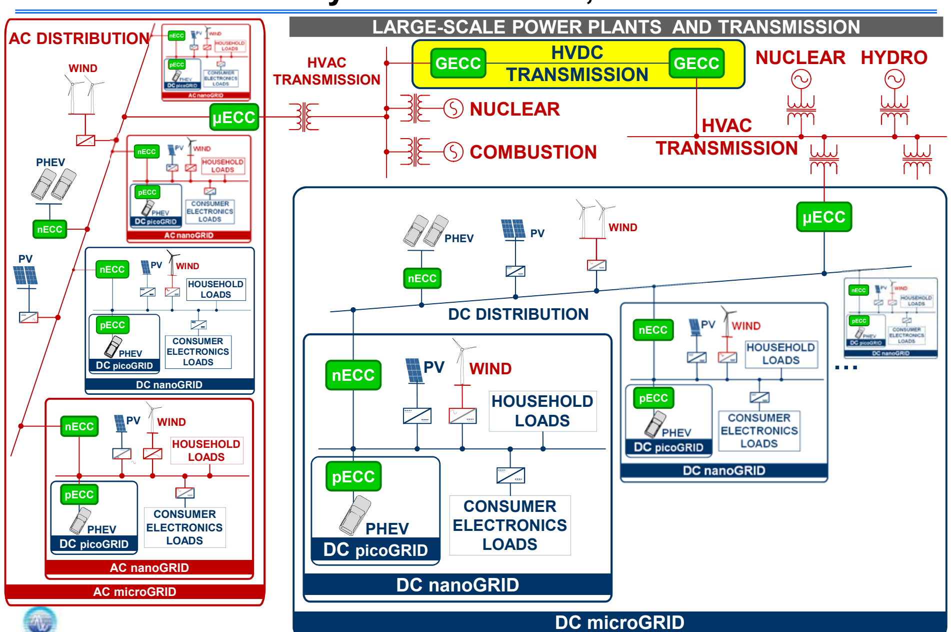
**Main features:**

- At least minimal level of local energy generation and storage;
- Interfaces to the higher-level system through bidirectional power converters;
- Ability to operate in islanded mode;
- Extensive communication and control capabilities;
- No thermo-mechanical switchgear;
- Step-up/down and isolation functions provided by the power converters (no low-frequency transformers);




CPES 2012.05.24 db-15a

## Intergrid: Hierarchical network of dynamically-decoupled, electronically-interconnected, sub-networks

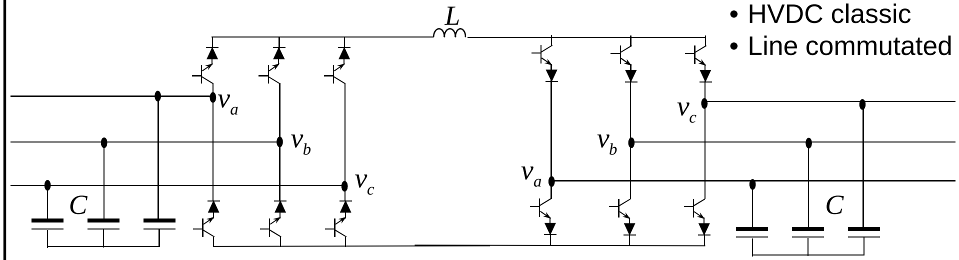



CPES 2012.05.24 db-15b

## Basic Topologies for High-Power ECCs

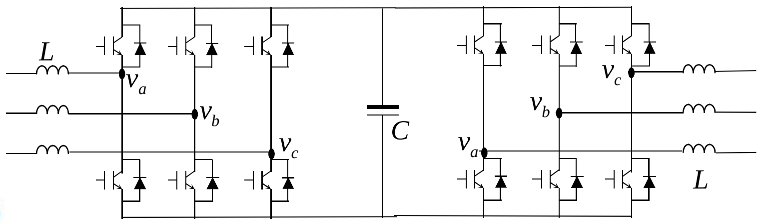
**Current Source Converter**

- Thyristor-based
- HVDC classic
- Line commutated




**Voltage Source Converter**

- IGBT-based
- HVDC light






## Recent Paper in *Proceedings of the IEEE*

Vol. 100, No. 2, February 2012 *

INVITED PAPER

# State of the Art in Ultrahigh-Voltage Transmission

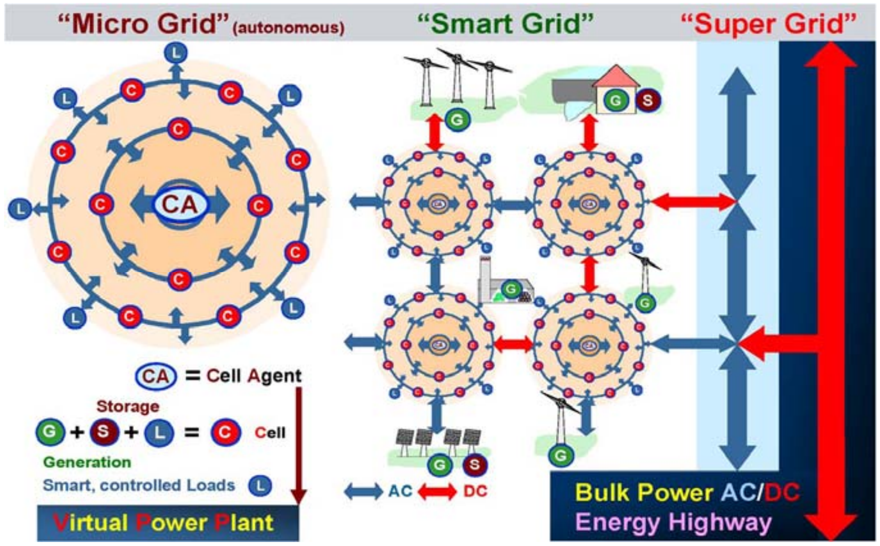
*This paper discusses ultrahigh-voltage (UHV) DC as an efficient solution for bulk power transmission, especially of renewable energy.*

By Thomas James Hammons, *Fellow IEEE*, Victor F. Lescale, *Life Member IEEE*, Karl Uecker, Marcus Haeusler, Dietmar Retzmann, *Member IEEE*, Konstantin Staschus, *Senior Member IEEE*, and Sébastien Lepy

 * Hammons, T. J. et al., "State of the Art in Ultrahigh-Voltage Transmission," *Proc. IEEE*, Vol. 100, No. 2, Feb. 2012. 

## *Fig. 10.* ***Prospects of grid developments.***

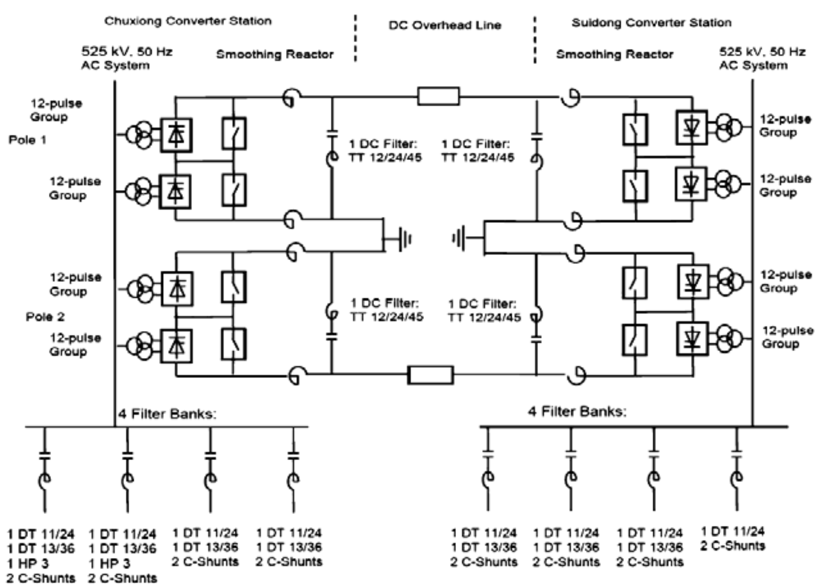
Hammons, T. J. et al., "State of the Art in Ultrahigh-Voltage Transmission," *Proc. IEEE*, Vol. 100, No. 2, Feb. 2012.




CPES 2012.05.24 db-18

## *Fig. 23.* ***Single line diagram of Yunnan-Guangdong UHV DC system.***

Hammons, T. J. et al., "State of the Art in Ultrahigh-Voltage Transmission," *Proc. IEEE*, Vol. 100, No. 2, Feb. 2012.




CPES 2012.05.24 db-19

***Fig. 26.* A view of the thyristor valve towers in the 800-kV valve hall.**

Hammons, T. J. et al., "State of the Art in Ultrahigh-Voltage Transmission," *Proc. IEEE*, Vol. 100, No. 2, Feb. 2012.

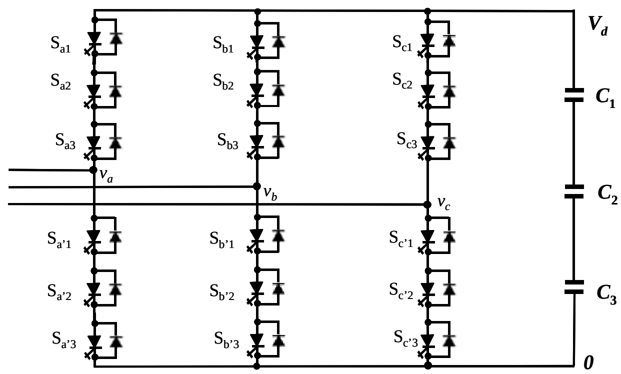

CPES 2012.05.24 db-20

***Fig. 27.* 800-kV converter transformer (single-phase two winding).**

Hammons, T. J. et al., "State of the Art in Ultrahigh-Voltage Transmission," *Proc. IEEE*, Vol. 100, No. 2, Feb. 2012.


CPES 2012.05.24 db-21

## Two-Level Converter for High-Voltage Applications

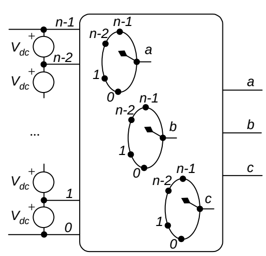


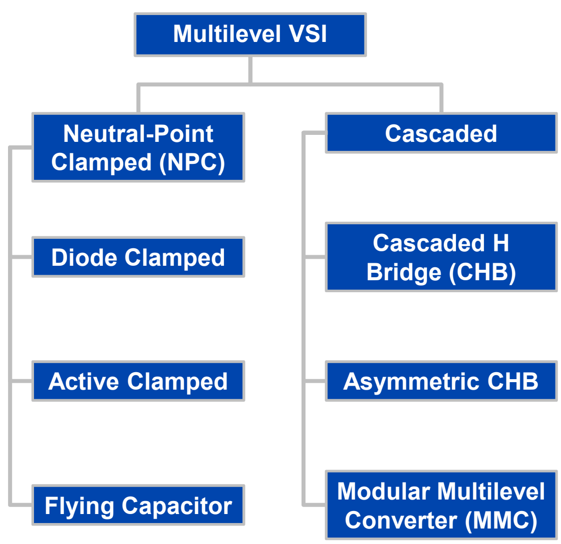

- Difficulty in voltage sharing among devices, especially the voltage sharing during switching transients.
- Needs complex active gate-drives to achieve voltage sharing.



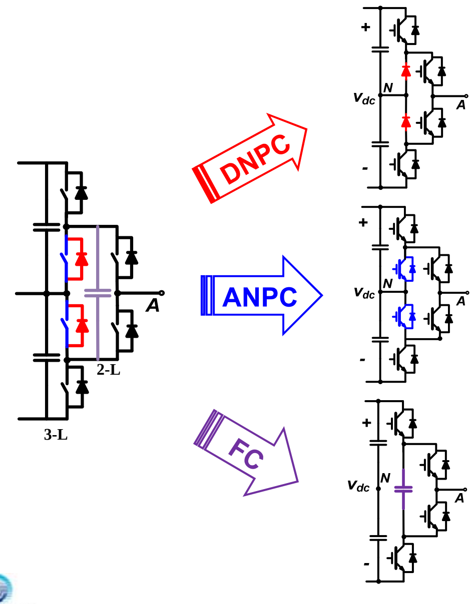
## Multilevel Converters for High-Voltage Applications

Functional diagram of Multilevel converter



## Multilevel Structures – Capacitor Clamped




**Diode Clamped**

- Uneven device losses
- Neutral point voltage balance

**Active Clamped**

- Even device losses with control
- Neutral point voltage balance

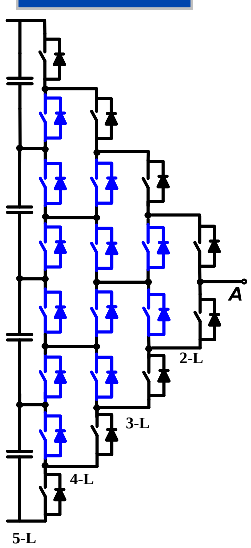
**Flying Capacitor**

- Uneven device losses
- Neutral point voltage balance
- Clamping cap voltage control

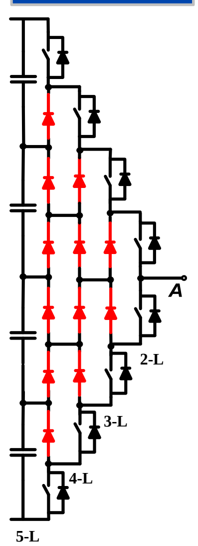


## Multilevel Structures – Capacitor Clamped

**5-level AC**




**5-level DC**




**m-level NPC**

DNPC

- Switches: 2× (m-1)
- Diodes: (m-1)×(m-2)

ANPC

- Switches: m×(m-1)

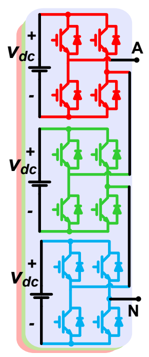
**Large number of devices**

**Complex structure**

**Cap. Voltage balancing**

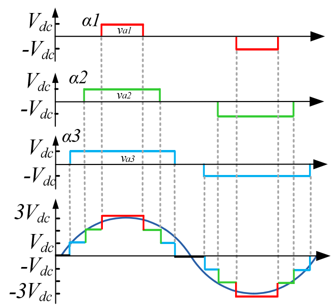
# Multilevel Structures – Cascaded H Bridge

**Symmetrical CHB**



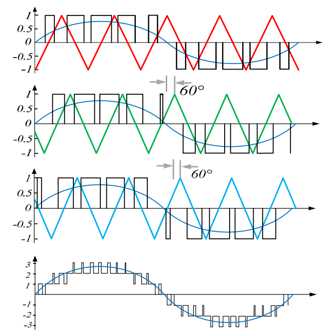

- Module: N
- Level: 2N+1

**Low Freq. Modulation**




- Loss reduction
- Four commutations
- Uneven conduction

**Phase Shift Modulation**



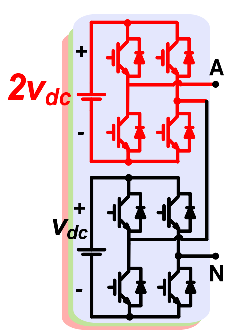

- THD reduction
- Uni-polar modulation
- Even Switching pattern

**Highly Scalable Structure** **Need Isolated DC Sources**

CPES 2012.05.24 db-26

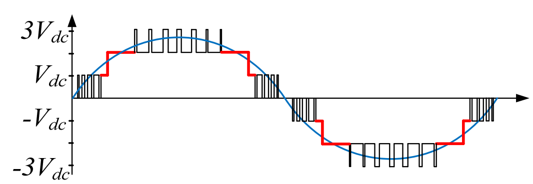
# Multilevel Structures – Cascaded H Bridge

**Asymmetrical CHB**




- Module: N
- Level: $2^{(N+1)}$-1

**Hybrid Modulation**



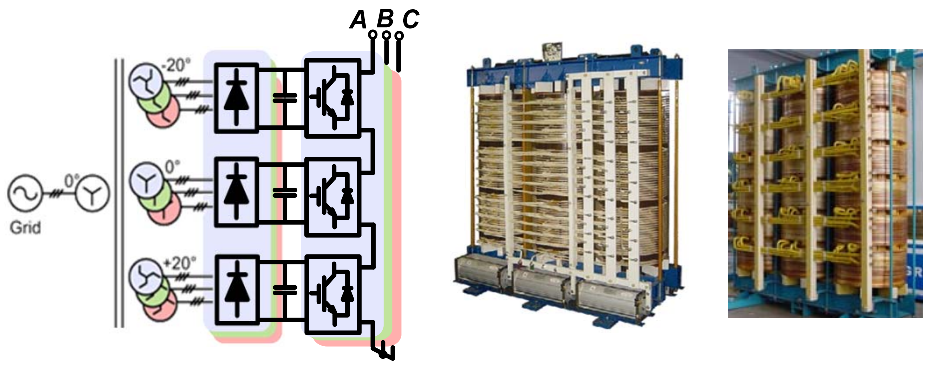

- Low freq. for high voltage module: loss reduction
- High freq. for low voltage module: THD reduction

**More levels produced** **Uneven loss & stress** **Loss of some modularity**

CPES 2012.05.24 db-27

## System Configurations for CHB

**Phase Shift Transformer for CHB**




- Line frequency magnetics
- Good input power quality
- Size, weight, cost issues
- Unidirectional operation

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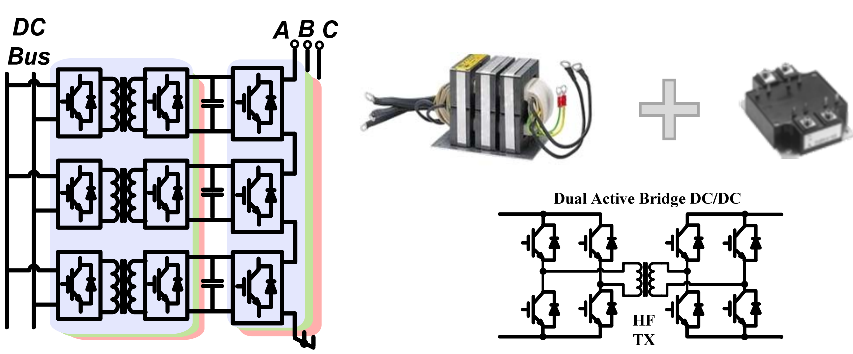
## System Configurations for CHB

**High Freq. Isolation for CHB**




- High freq. magnetics
- Smaller Size
- Bidirectional Operation
- Highly Scalable
- Extra switches & circuits
- High switching loss

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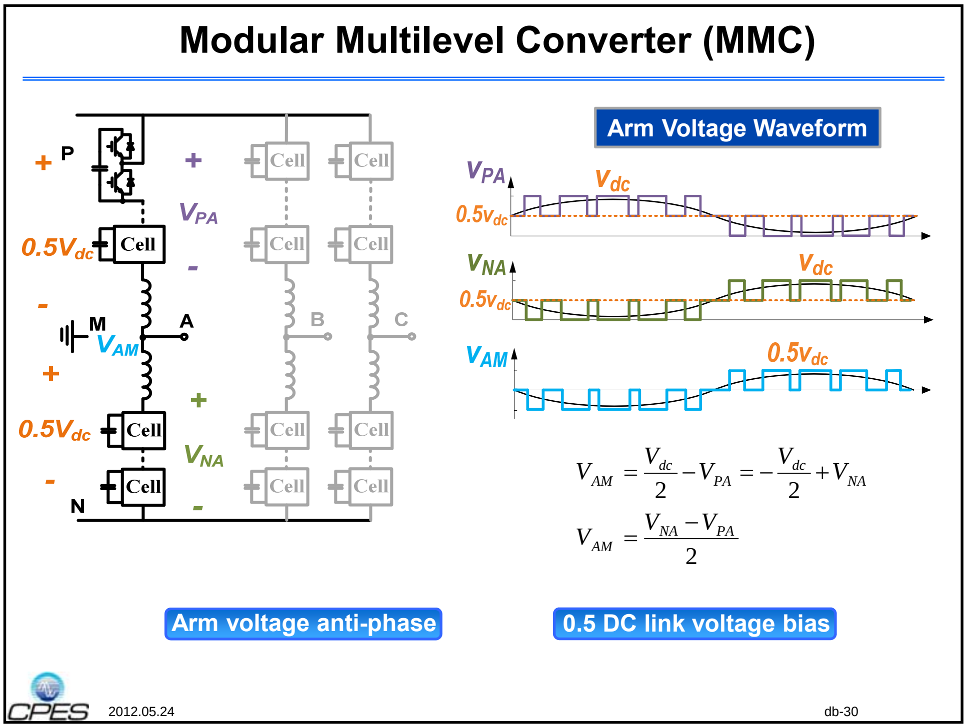

Modular Multilevel Converter (MMC)
Arm Voltage Waveform
P
M
N
A
B
C
Cell
$V_{PA}$
$V_{NA}$
$V_{AM}$
$0.5V_{dc}$
$V_{dc}$
$V_{AM} = \frac{V_{dc}}{2} - V_{PA} = -\frac{V_{dc}}{2} + V_{NA}$
$V_{AM} = \frac{V_{NA} - V_{PA}}{2}$
Arm voltage anti-phase
0.5 DC link voltage bias
CPES
2012.05.24
db-30

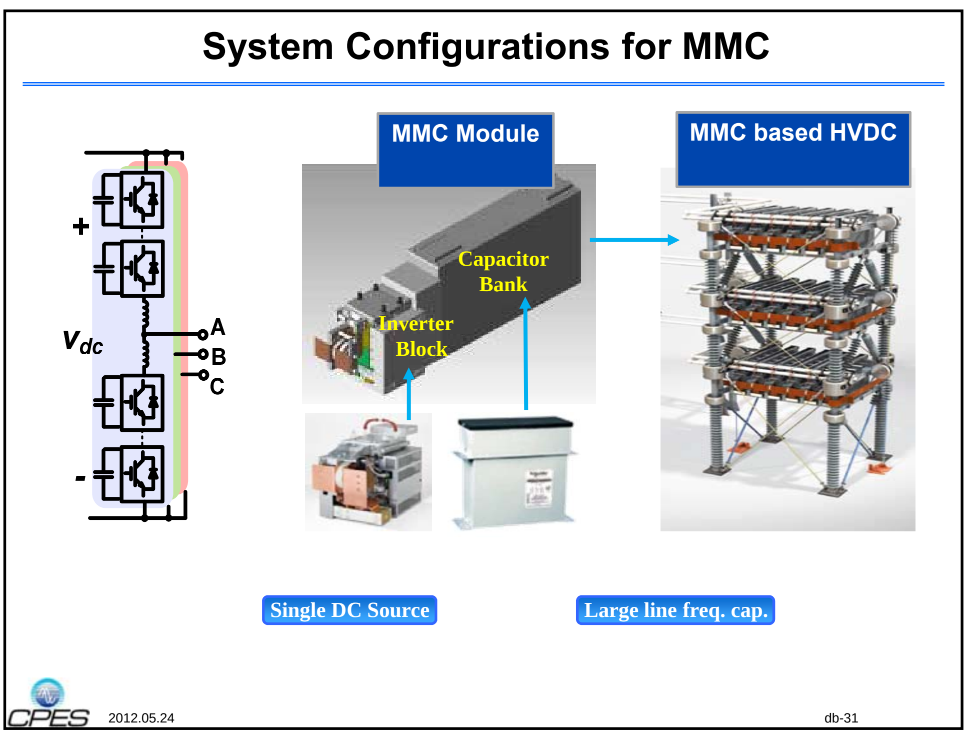
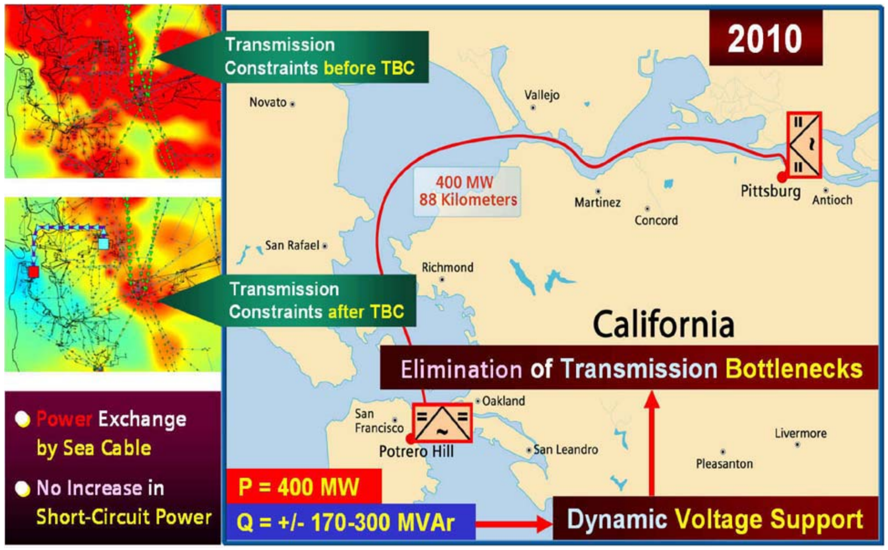
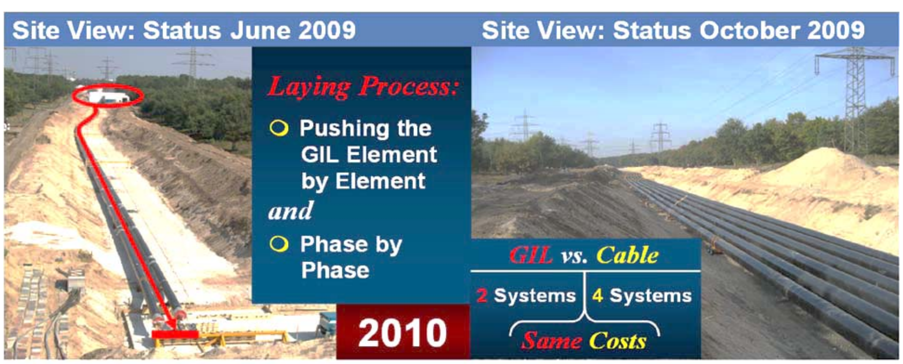

System Configurations for MMC
MMC Module
MMC based HVDC
Capacitor Bank
Inverter Block
$V_{dc}$
A
B
C
Single DC Source
Large line freq. cap.
CPES
2012.05.24
db-31

***Fig. 14.* The "Trans Bay Cable" project in the United StatesVworld's first VSC HVDC with MMC technology and þ=200-kV XLPE cable. ***




CPES 2012.05.24 * Hammons, T. J. et al., "State of the Art in Ultrahigh-Voltage Transmission," *Proc. IEEE*, Vol. 100, No. 2, Feb. 2012. db-32

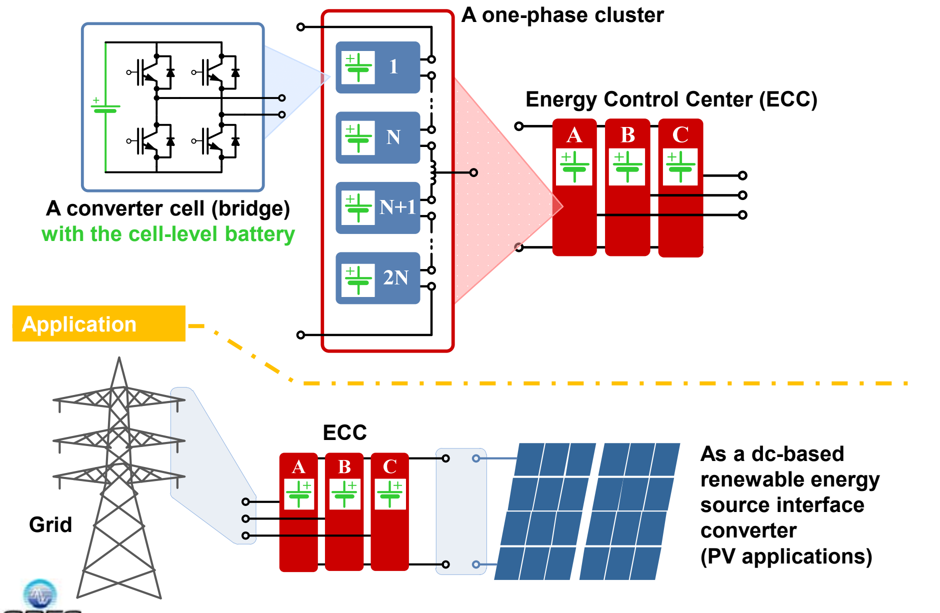
***Fig. 21.* Bulk Power Corridor with GILV400-kV installation at Kelsterbach, Germany. ***




- Customer: Amprion
- Location: Airport Frankfurt
- Award of Contract: July 2008
- Installation: first directly buried GIL
- Transmission Capacity: 2 x 1,800 MVA
- Length of GIL: appr. 1 km
- Gas for Insulation: 80% N2, 20%SF6

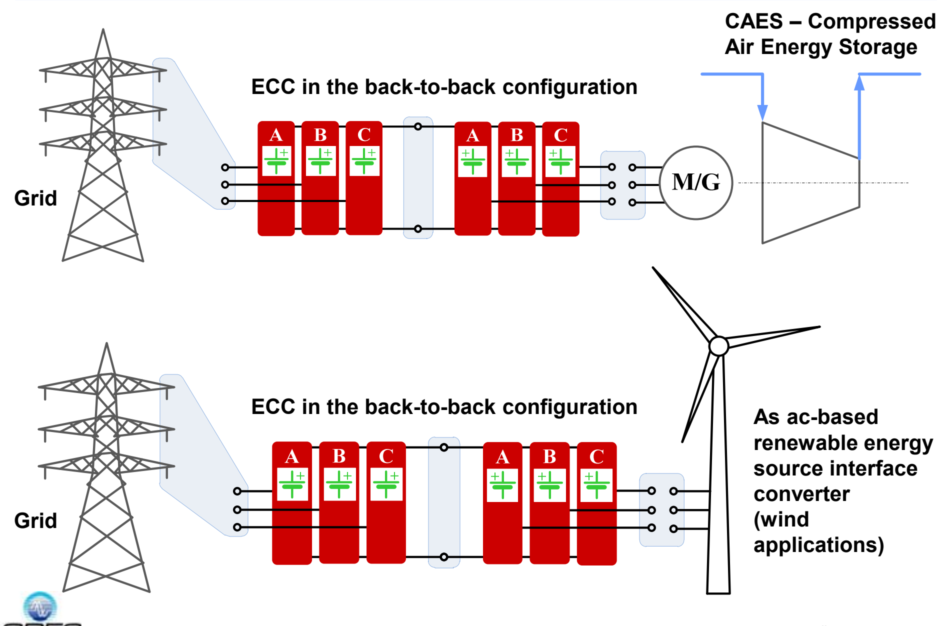
CPES 2012.05.24 * Hammons, T. J. et al., "State of the Art in Ultrahigh-Voltage Transmission," *Proc. IEEE*, Vol. 100, No. 2, Feb. 2012. db-33

## Modular Multi -Megawatt /-Cell /-Level Energy Storage-Interface Converter




CPES 2012.05.24 db-34

## Modular Multi -Megawatt /-Cell /-Level Energy Storage-Interface Converter

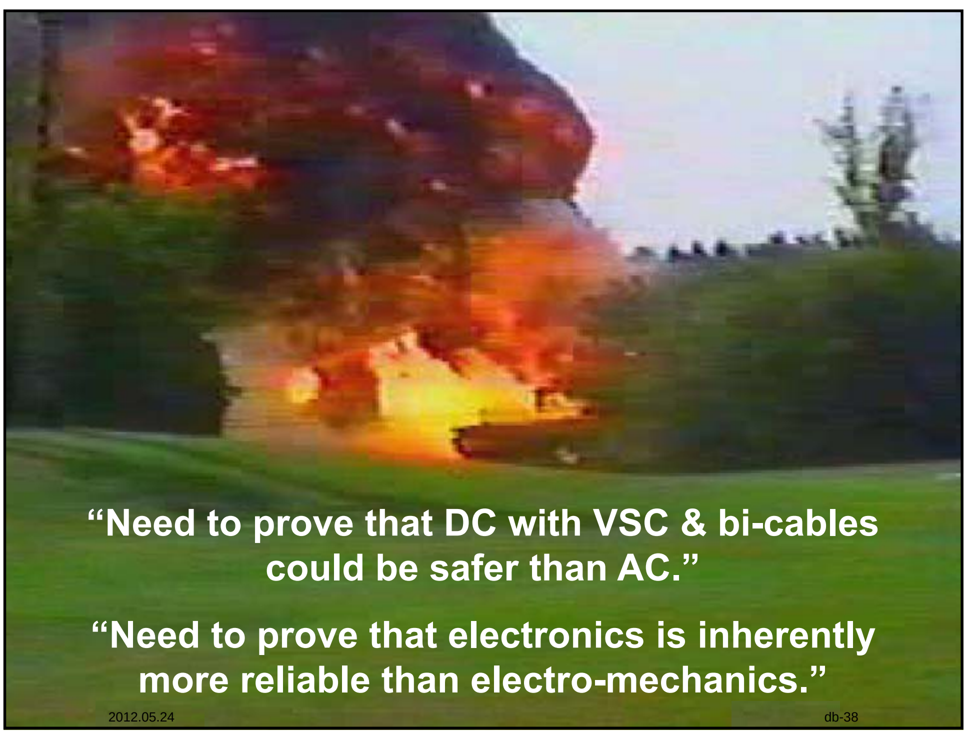



CPES 2012.05.24 db-35

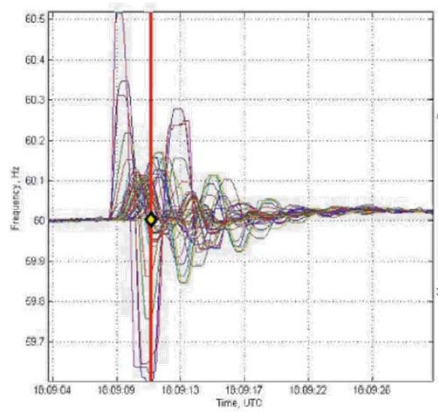
## Research Needed to **Replace Electric Energy "Railways" with "Highways"**

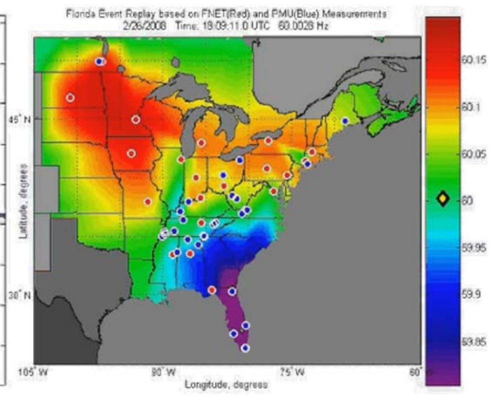
1. **Network Architectures and Control**
   - Hierarchical network of dynamically-decoupled, electronically-interconnected, sub-networks
   - Distributed generation, storage, loads, and intelligence
   - Continuous control of all energy flows
   - Enabling of efficient market mechanisms
2. **High-Power and High Power-Density Converters**
   - New materials, active and passive devices, thermal management
   - High-density integration and packaging, especially HIGH-VOLTAGE technologies and UNDERGROUND transmission / distribution
3. **Safety and Reliability**
   - Safety & protection (need to prove that DC with VSC & bi-cables could be safer than AC)
   - Reliability & lifetime (need to prove that electronics is inherently more reliable than electro-mechanics)
   - Security and availability (need to prove that decoupled networks are inherently more robust and resilient)

CPES 2012.05.24 db-36



## Frequency Variations during 2008 Florida Blackout




**"Need to prove that decoupled networks are inherently more robust and resilient."**

CPES 2012.05.24 db-37

## Education Needed to Instigate Innovative Intellectual "Ecosystem"

1. **Network Architectures**
   - Hierarchical network of dynamically-decoupled, electronically-interconnected, sub-networks
   - Distributed generation, storage, loads, and intelligence
2. **Energy Transfer Protocols and Markets**
   - Continuous control of all energy flows
   - Enabling of efficient market mechanisms

**Computational infrastructure for hierarchical, multidisciplinary, multiscale modeling, analysis, design, and optimization**

3. **High-Power and High Power-Density Converters**
   - New materials, active and passive devices, thermal management
   - High-density integration and packaging
4. **Safety and Reliability**
   - Safety & protection
   - Reliability & lifetime

**Experimental infrastructure for Hierarchical low- to high-power validation of electronic control of energy traffic**

**Need new engineers = power + electronics**

CPES 2012.05.24 db-39

Dave

Grider

# Advanced SiC Power Technology for High Megawatt Power Conditioning

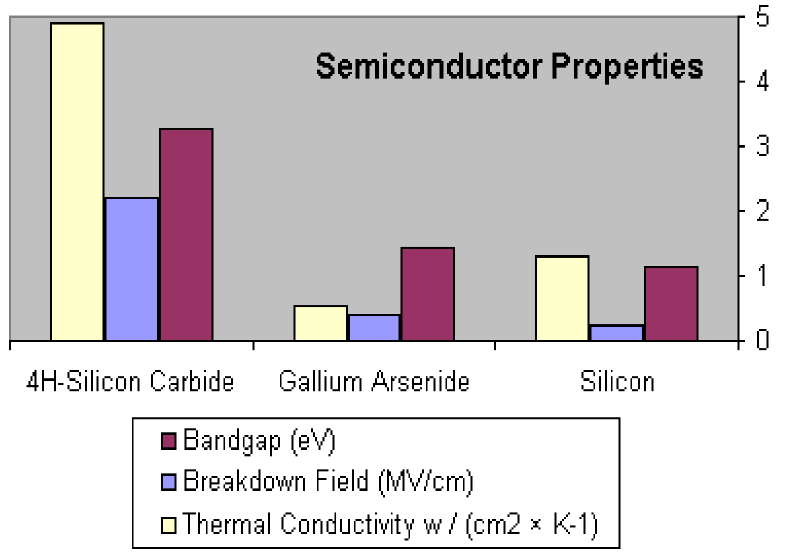
*David Grider, Anant Agarwal, Sei-Hyung Ryu, Lin Cheng, Craig Capell, Charlotte Jonas, Al Burk, Michael O'Loughlin, Mrinal Das, John Palmour*

**Cree, Inc.**

*May 24, 2012*

# Why SiC Power?
# SiC's Material Difference

- **10X Breakdown Field of Si**
  - Lower specific on-resistance and faster switching for the same breakdown voltage
- **3X Thermal Conductivity of Si**
  - Higher current densities
- **3X Bandgap of Si**
  - Higher temperature operation



For more than 60 years, silicon has been the "go-to" material for power semiconductors.

But in terms of delivering additional efficiency, silicon is nearing its limit.

**{ Thank you silicon—we'll take it from here. }**

## Silicon Carbide is the most efficient and highest reliability power semiconductor material in the world today

## —and it will power our future.

MOTOR & MOTION CONTROL SOLAR TRACTION WIND ENERGY SERVERS AND MANY MORE

# Cree Commercial SiC Power Product Portfolio

## ZERO RECOVERY™ Rectifier Product Family

**600V Z-Rec SiC JBS Diodes**
**1, 2, 3, 4, 6, 8, 10 & 20**

**650V Z-Rec SiC JBS Diodes**
**4, 6, 8, 10 & 20A**

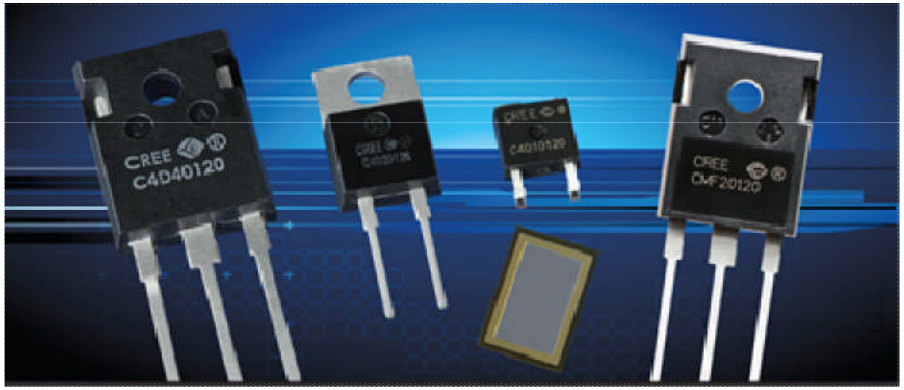
**New! Z-Rec 1200V SiC JBS Diodes**
**2, 5, 7.5, 10, 15, 20, 30 & 40A**

**1200V SiC JBS Diodes**
**5, 10, 20 & 50A**

**1700V Z-Rec SiC JBS Diodes**
**10 & 25A**

## The Z-FET™ MOSFET Product Family

**1200V SiC DMOSFET**
**80mΩ & 160mΩ available today**

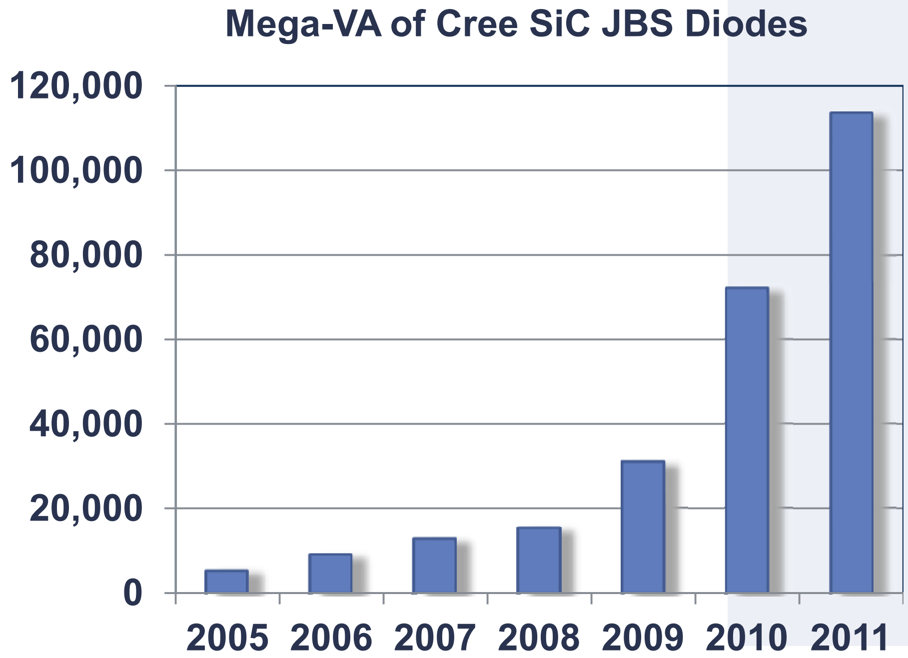


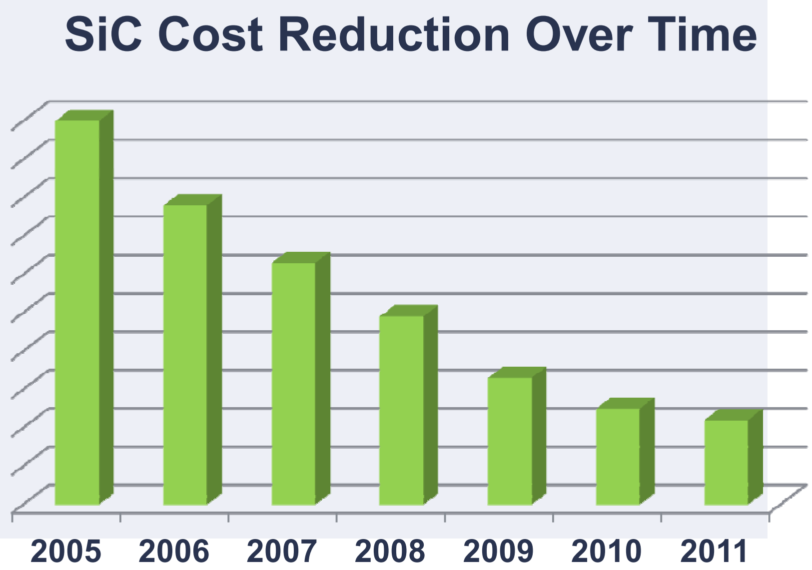

## Packages

**THROUGH HOLE: TO-247 TO-220,**
**Fully molded TO-220,**
**SMT: TO-252 (D-Pak), TO-263 ($D^2$-Pak)**

# Cree Commercial JBS Diode Production

- In FY2011 Cree Shipped >113 GVA
  - 61% Increase Over 2010
  - 66% CAGR Since 2005
- Over 5x Cost Reduction Result of 3 Factors
  - Higher Quality SiC Material
  - Larger Production Volumes
  - SiC Wafer Size Increased From 3 inch to 100 mm Diameter



# Industry-Lowest Field Failure Rate of Cree SiC JBS Diodes

## Cree Field Failure Rate Data since Jan. 2004

| Product | Device Hours | FIT (fails/billion hrs) |
|---|---|---|
| CSDxxx60 | 205,000,000,000 | 0.16 |
| C3Dxxx60 | 81,000,000,000 | 0.09 |
| C2Dxx120 | 46,000,000,000 | 1.35 |
| **Total** | **332,000,000,000** | **0.31** |

- **This rate is 10 times lower than the typical silicon**

**330 billion device hours in the field with an industry-leading FIT rate of only 0.31**

# Z-FET™

## Industry's First SiC MOSFET Available in Volume Production

# CMF20120D-Silicon Carbide Power MOSFET

*Z-FET™ MOSFET*

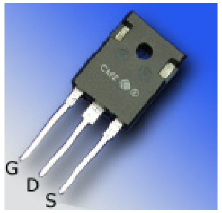
N-Channel Enhancement Mode

| | |
|---|---|
| $V_{DS}$ | = 1200 V |
| $R_{DS(on)}$ | = 80 mΩ |
| $I_{D(MAX)}$ @$T_c$=25°C | = 33 A |

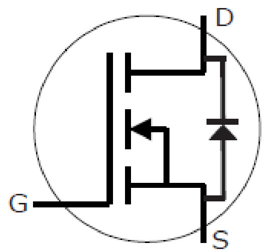
## Features

- Industry Leading $R_{DS(on)}$
- High Speed Switching
- Low Capacitances
- Easy to Parallel
- Simple to Drive
- Pb-Free Plating, RoHS Compliant, Halogen Free

## Package




TO-247-3




## Benefits

- Higher System Efficiency
- Reduced Cooling Requirements
- Avalanche Ruggedness
- Increased System Switching Frequency

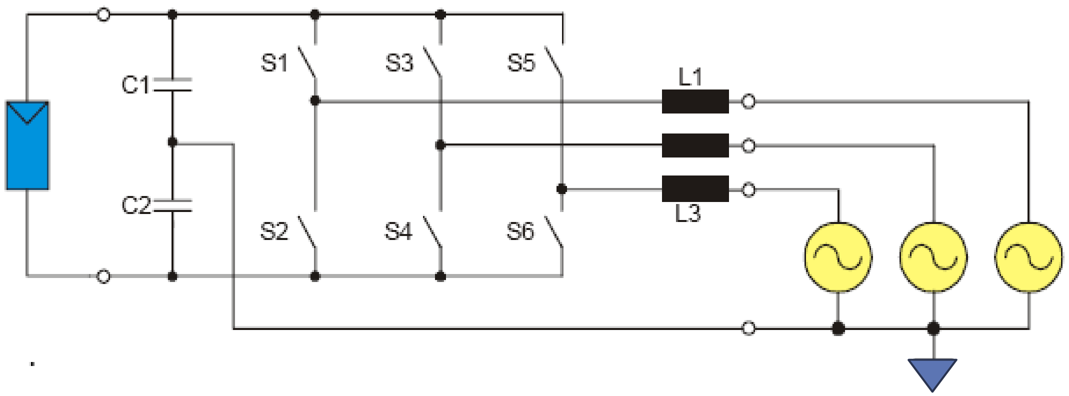
| Part Number | Package |
|---|---|
| CMF20120D | TO-247-3 |

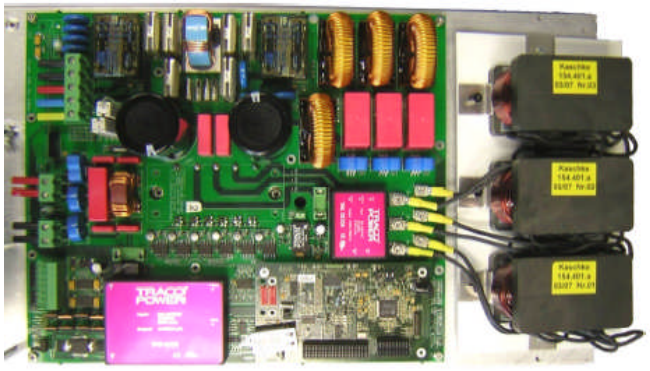
## Applications

- Solar Inverters
- High Voltage DC/DC Converters
- Motor Drives

**Avalanche Energy = 2.2 J**

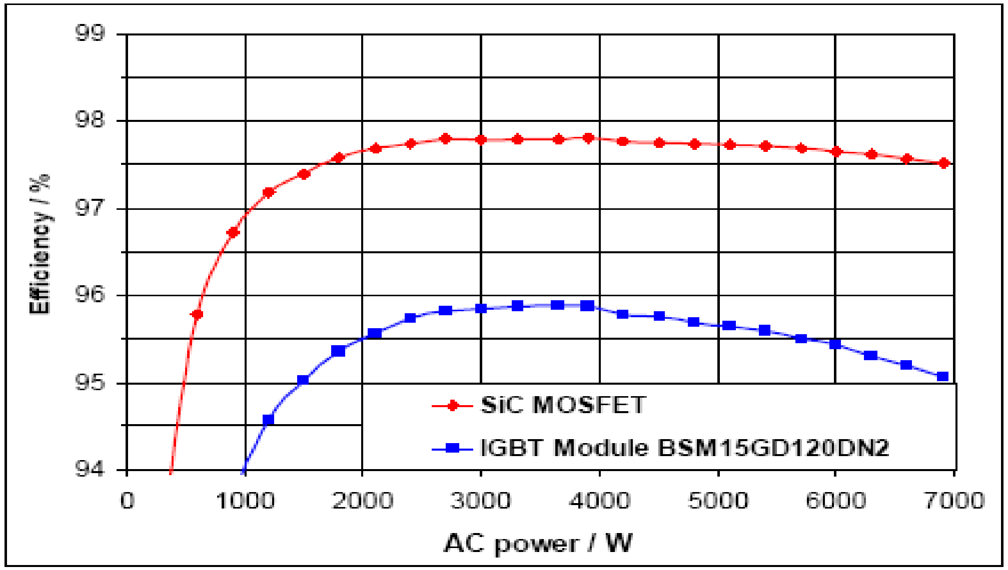
# Solar Inverter Example Using 1200 V/20A SiC MOSFETs



**7kW 750V DC link 3-Phase Solar Inverter**

**(Fraunhofer Institute, Freiberg Germany)**




**~ 2% Efficiency Improvement vs. Si IGBT**

**Record PV efficiency since demonstrated at 99.05% with SiC power devices**

# 1200V SiC MOSFET Results in Dramatic Improvement in APEI All-SiC Inverter

### Actual Size Comparison

Heat Sink

28"

14"

7"

| Characteristics | Commercial Si Inverter | APEI, Inc. SiC Inverter | Comparison |
|---|---|---|---|
| Power | 5 kW | 5 kW | Same |
| Cooling | Free Air Convection | Free Air Convection | Same |
| Peak Efficiency @ Pk Power | 95.50% | 96.75% | APEI increased efficiency 1.25% |
| Power Loss | 205 watts | 162 watts | APEI reduces losses 27% |
| Size | 28.5" x 16" x 5.75" | 4.5" x 9" x 9" | APEI > 7x smaller volume |
| Volume | 2,622 cubic inches | 365 cubic inches | APEI > 7x smaller volume |
| Mass | 58 lbs. | 7.25 lbs. | APEI > 8x lighter |
| Pk Temperature Capability | < 125 °C | > 225 °C | APEI 2x temperature capability |

Heat Sink


**Commercial**
**Si Inverter**

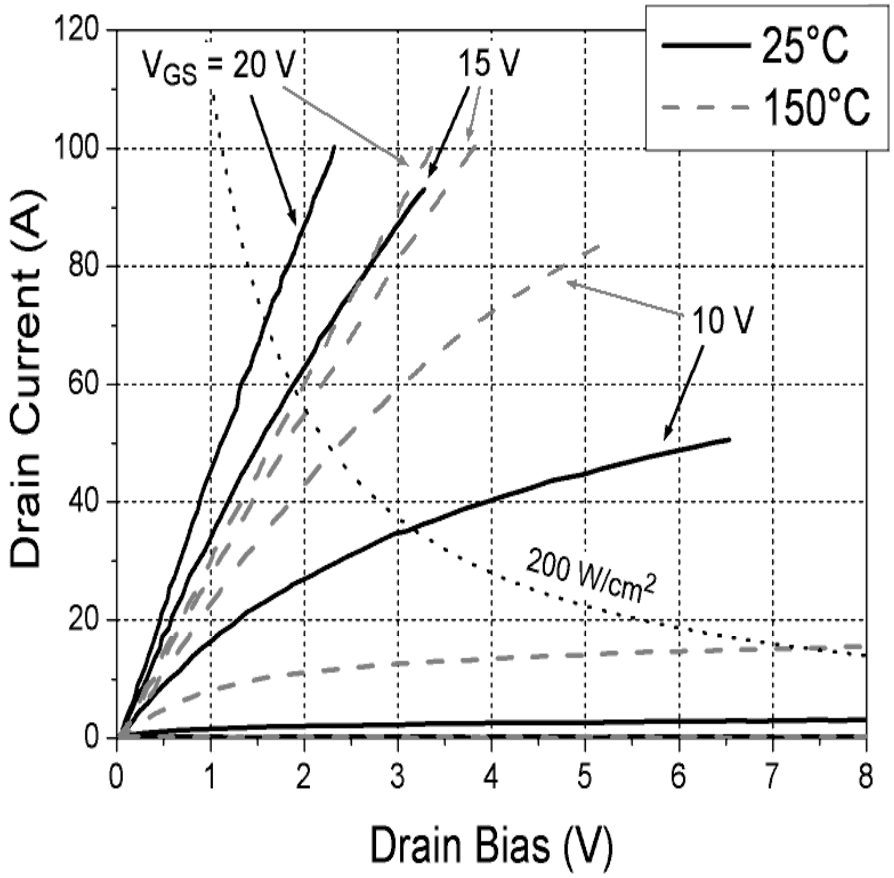
**APEI, Inc.**
**SiC Inverter**

All-SiC inverter
- operates at 225C
- 7x smaller
- 8x lighter
- has 27% lower losses

# 1200V Gen2 SiC DMOSFET With Dramatically Reduced On-Resistance

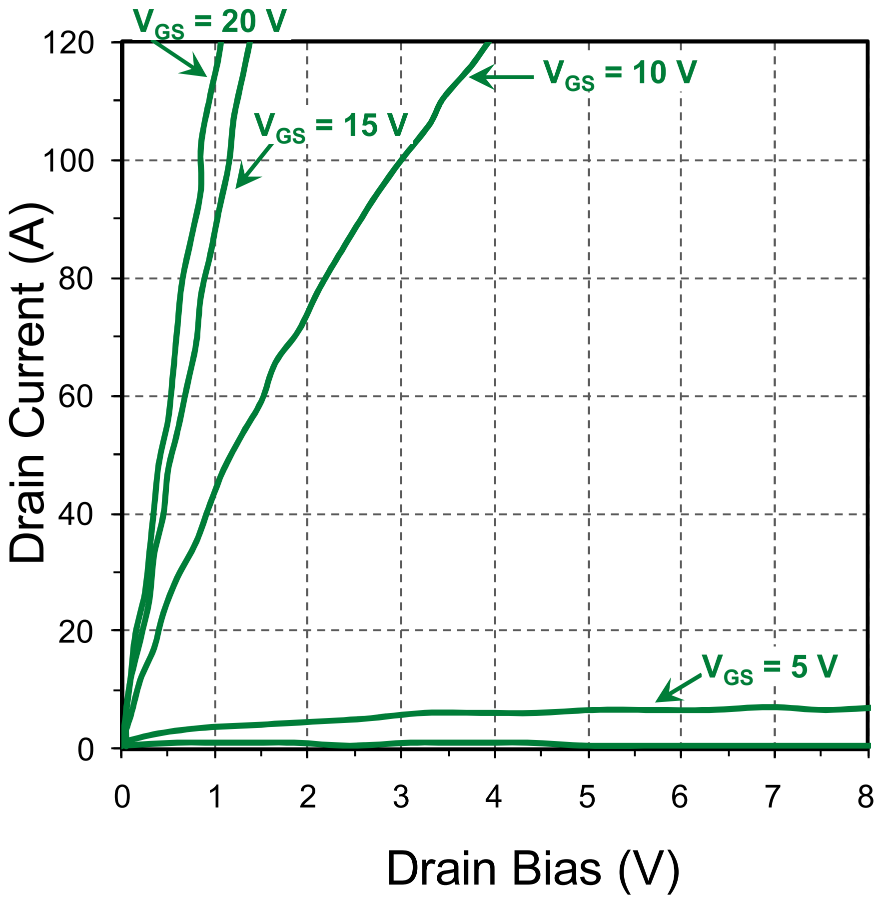
## Forward I-V characteristics

### 1200 V Gen1 SiC DMOSFET




$R_{sp,on}$ = 9.0 mΩ-cm² at $V_{GS}$ = 20V

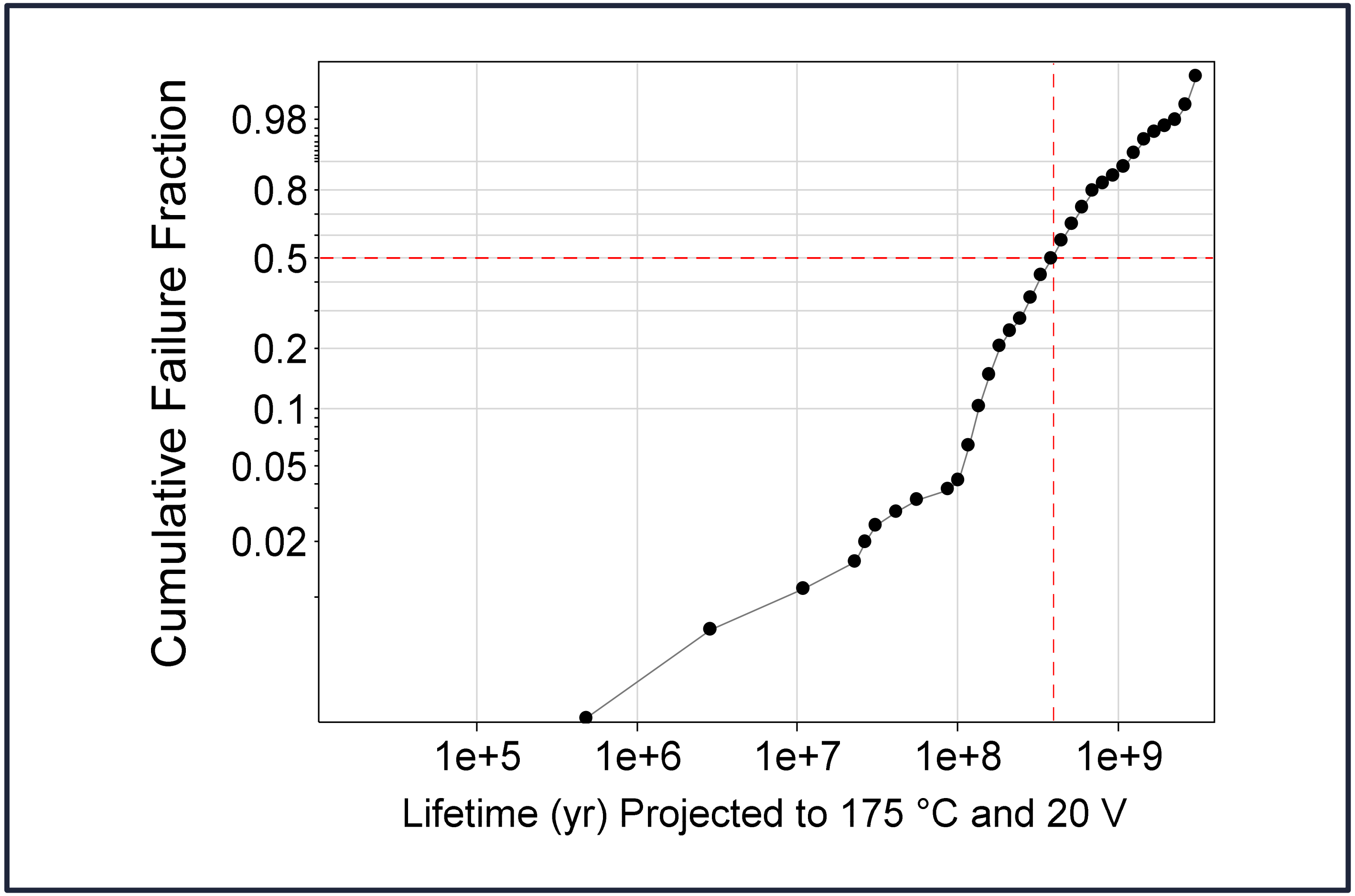
### 1200 V Gen2 SiC DMOSFET




$R_{sp,on}$ = 3.6 mΩ-cm² at $V_{GS}$ = 20V

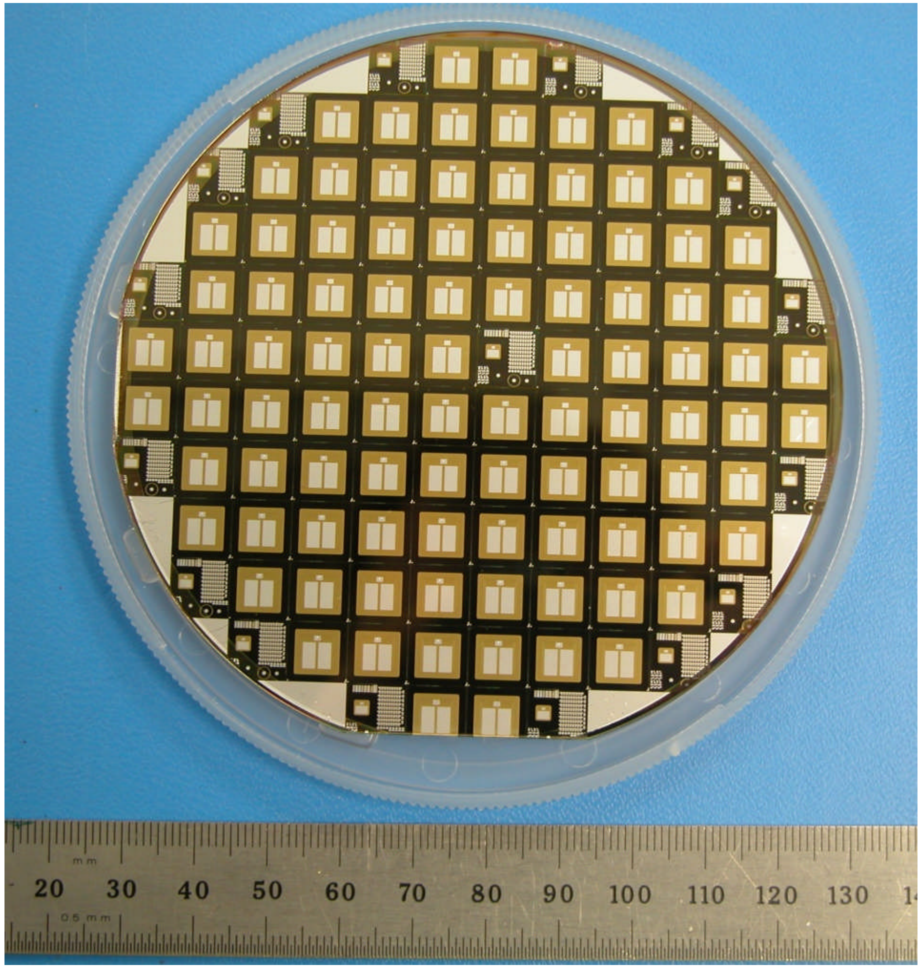
# Reliability of Cree's SiC Gate Oxide for SiC MOSFETs

## Ramped TDDB at 175°C

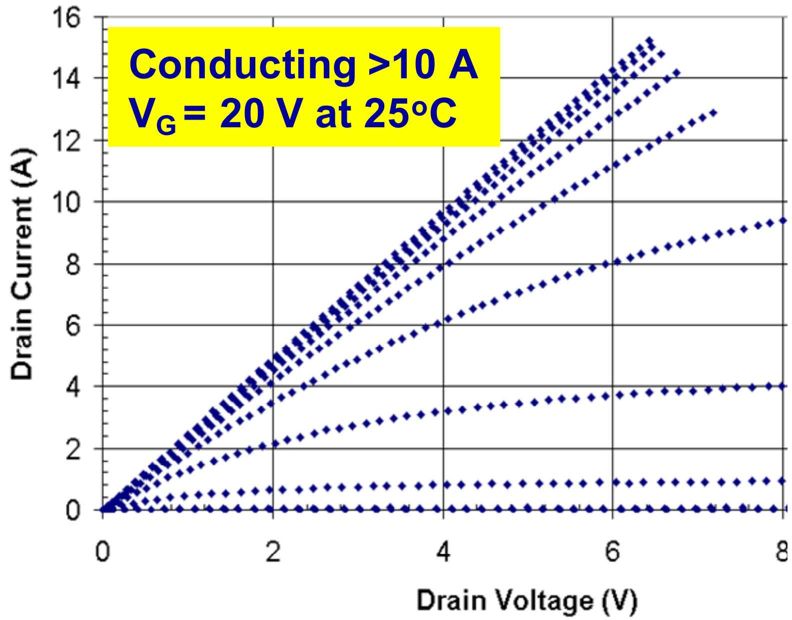


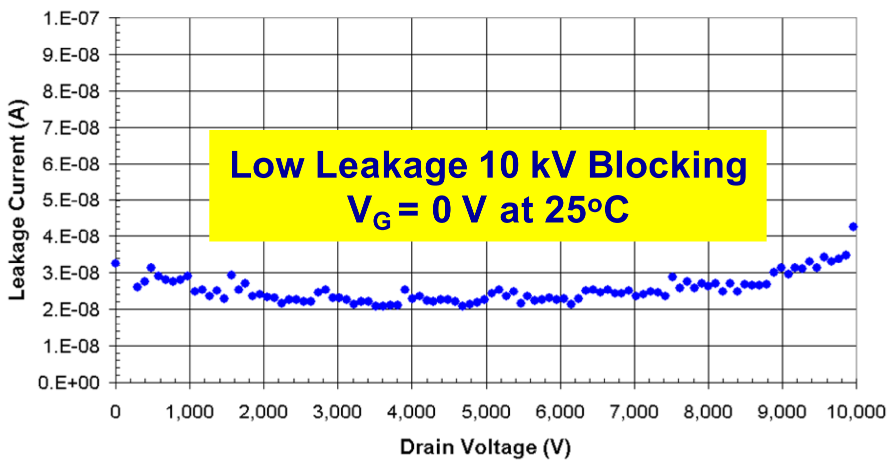

- **Projects to a MTTF of ~ 400 million years for SiC MOS capacitors at $V_{GS}$ = 20 V gate bias**

# 10 kV/10 A SiC DMOSFETs Developed Under DARPA/ONR HPE Program

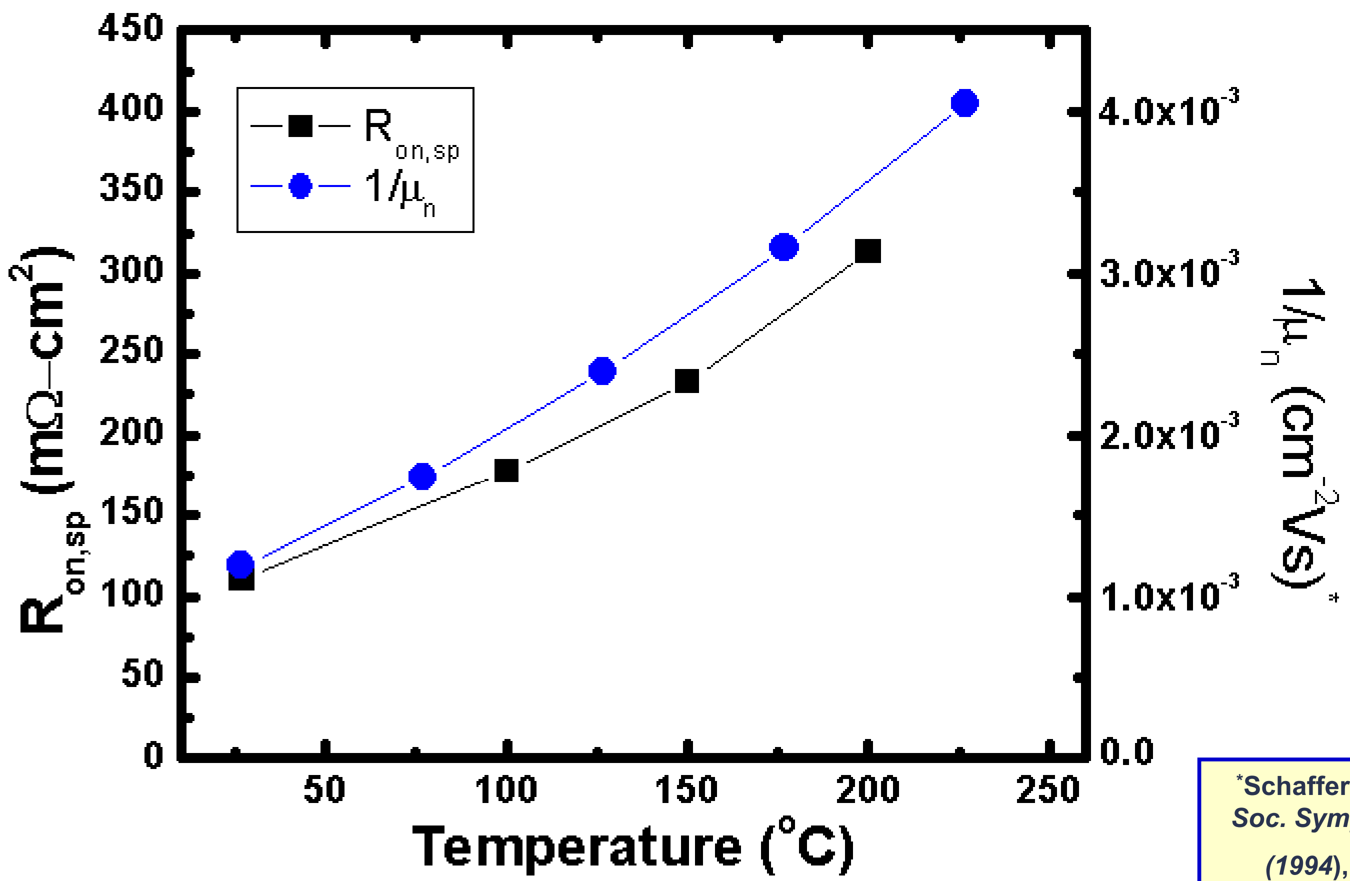



10 kV/10 A SiC DMOSFETs
Fabricated on 100 mm 4HN-SiC Wafer



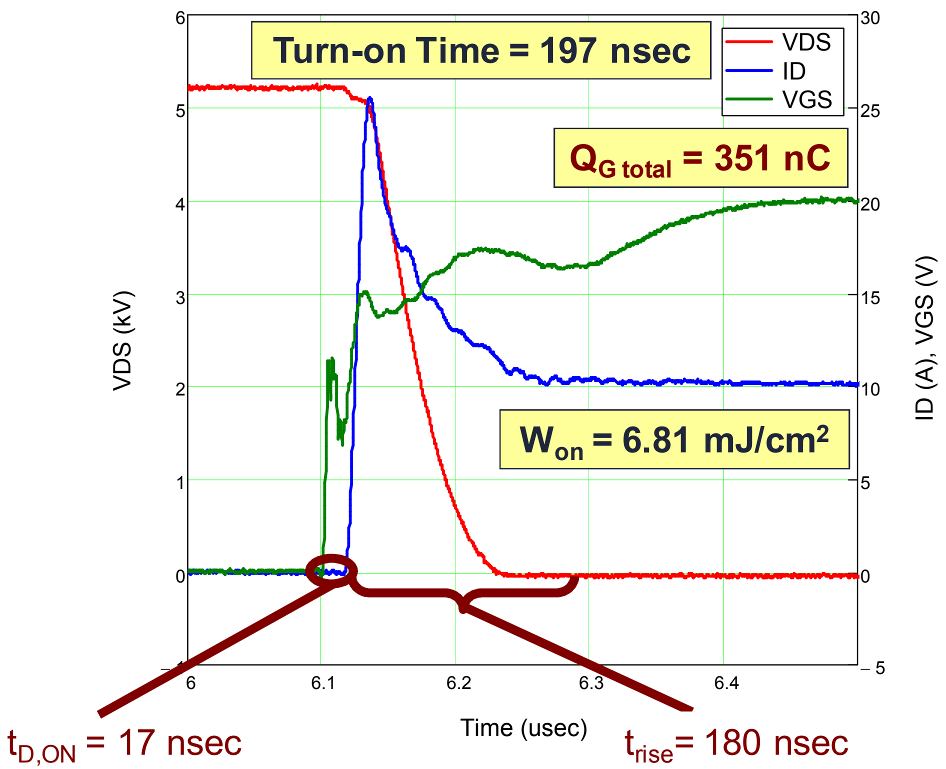
# 10kV/10A SiC DMOSFET On-Resistance vs. Temperature - Means Good Current Sharing Between Devices in Parallel



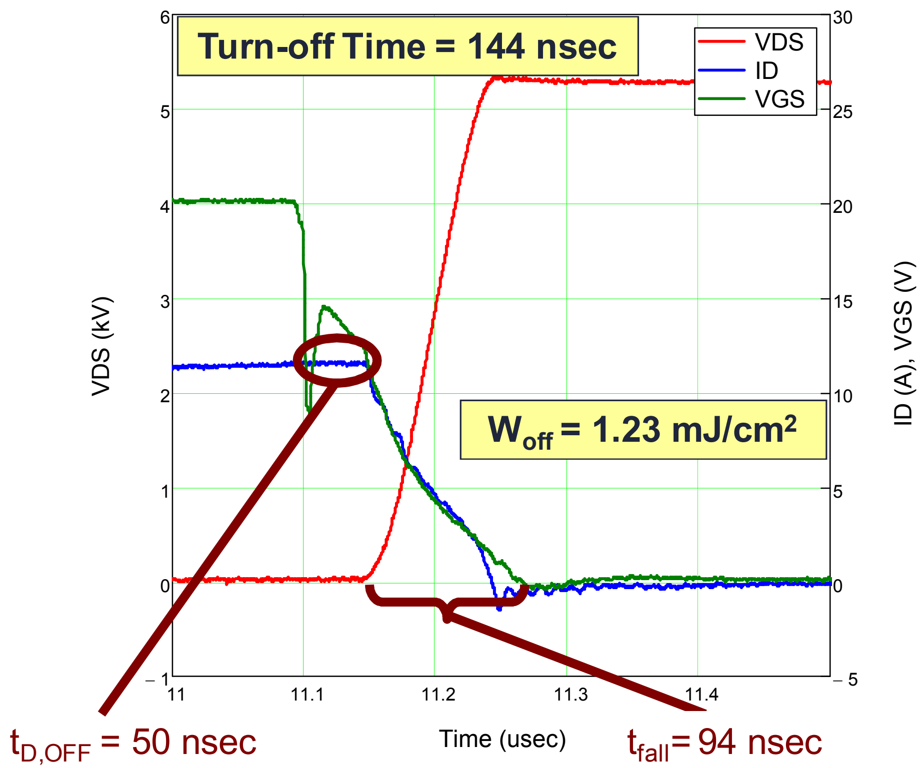

*Schaffer et al., *Mat. Res. Soc. Symp. Proc. Vol. 339 (1994)*, pp. 595 – 600

***$R_{on,sp}$ increases about 3x with a temperature increase to 200°C***
***Increase dominated by drift layer resistance***

# 10 kV/10 A SiC DMOSFET Clamped Inductive Switching




**10 kV/10 A SiC DMOSFET Turn-On Waveform**



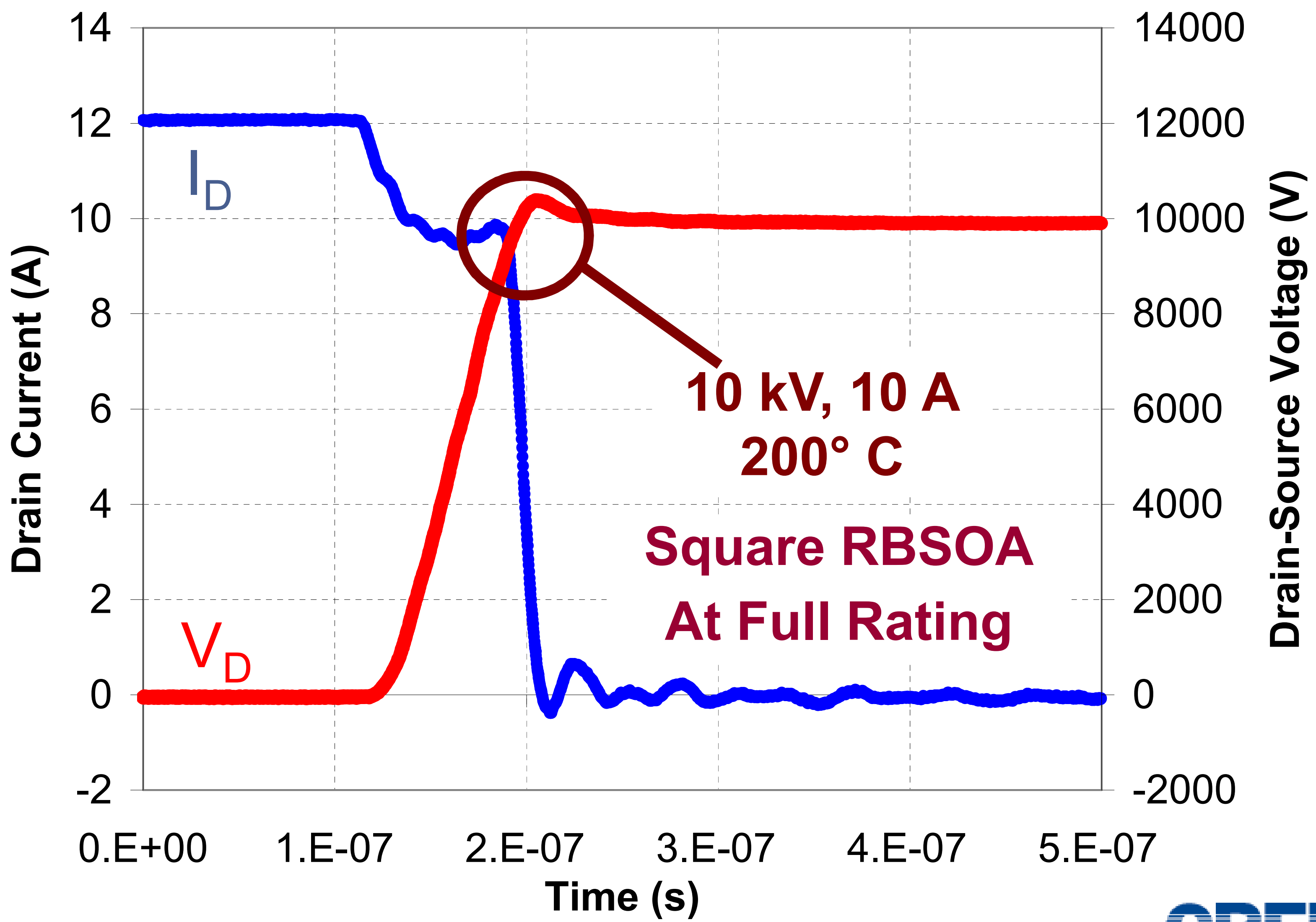

**10 kV/10 A SiC DMOSFET Turn-Off Waveform**

# Power Loss Comparison Between SiC 10 kV Switches and Si IGBTs

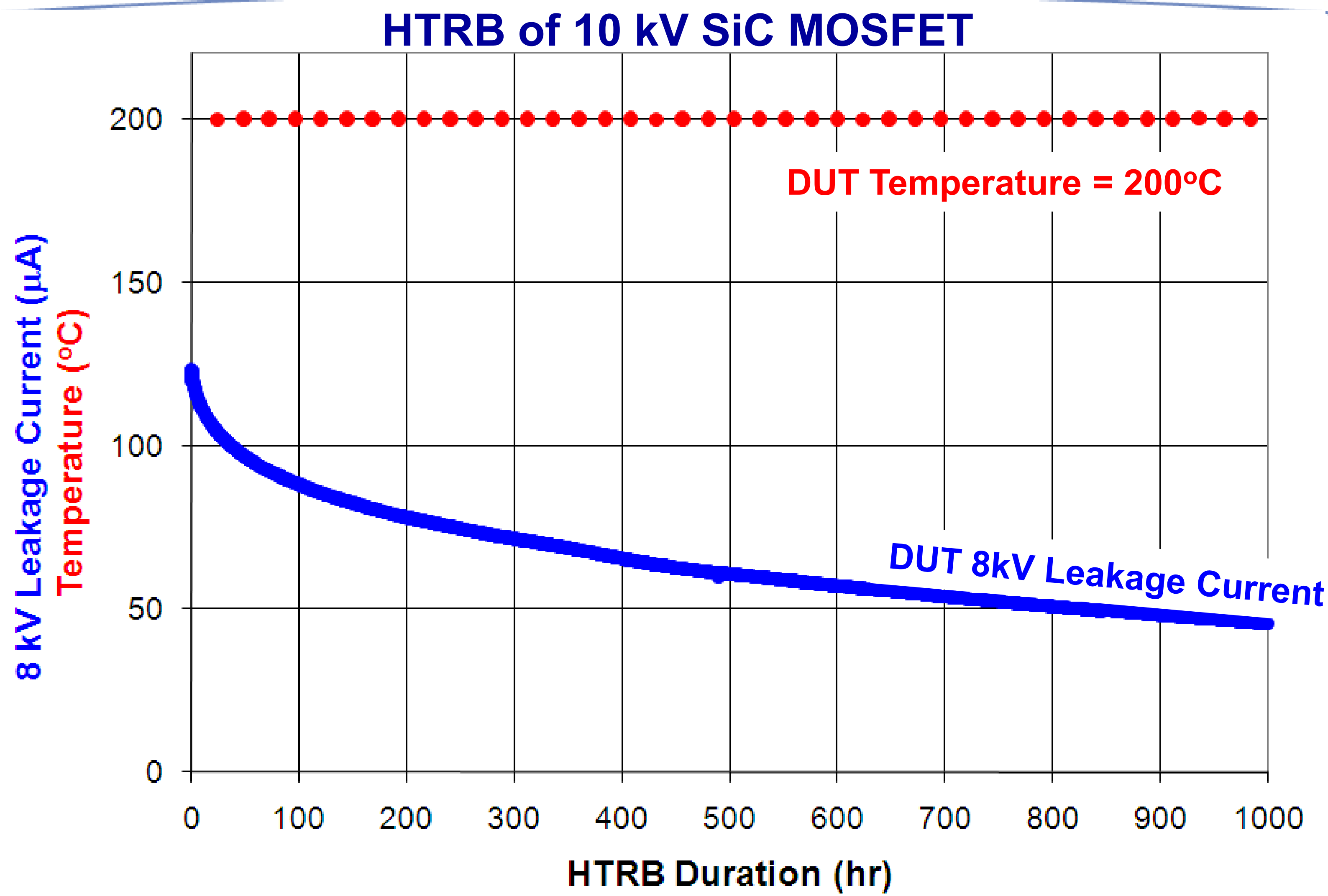
| Device | BV (kV) | 500 Hz 5 kV $P_{sw,sp}$ (W/cm²) | 5 kHz 5 kV $P_{sw,sp}$ (W/cm²) | 20 kHz 5 kV $P_{sw,sp}$ (W/cm²) | 33 A/cm² 50% Duty 100°C $P_{cond,sp}$ (W/cm²) |
|---|---|---|---|---|---|
| Cree SiC DMOSFET | 10 | 4 | 40 | 160 | 100 |
| Cree SiC n-IGBT | 12 | 6.5 | 65 | 260 | 66 |
| ABB Si IGBT 5SMX 12M6500 | 2x 6.5 | 72.5 | 725 | 2900 | 182 |

# Excellent Reverse Bias Safe Operating Area For 10 kV/10 A SiC DMOSFET

Courtesy: Dr. Allen Hefner, NIST



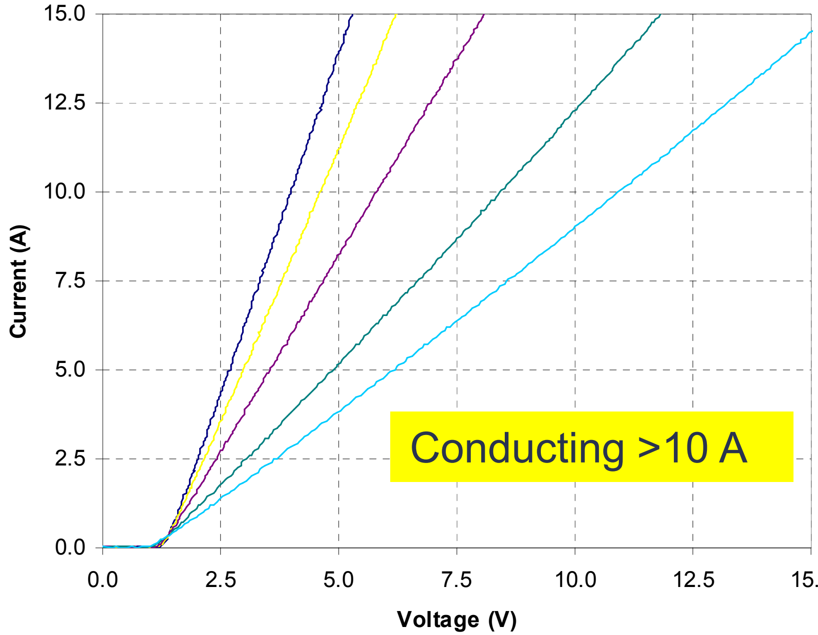
# Off-State Blocking Reliability Of 10 kV SiC DMOSFET

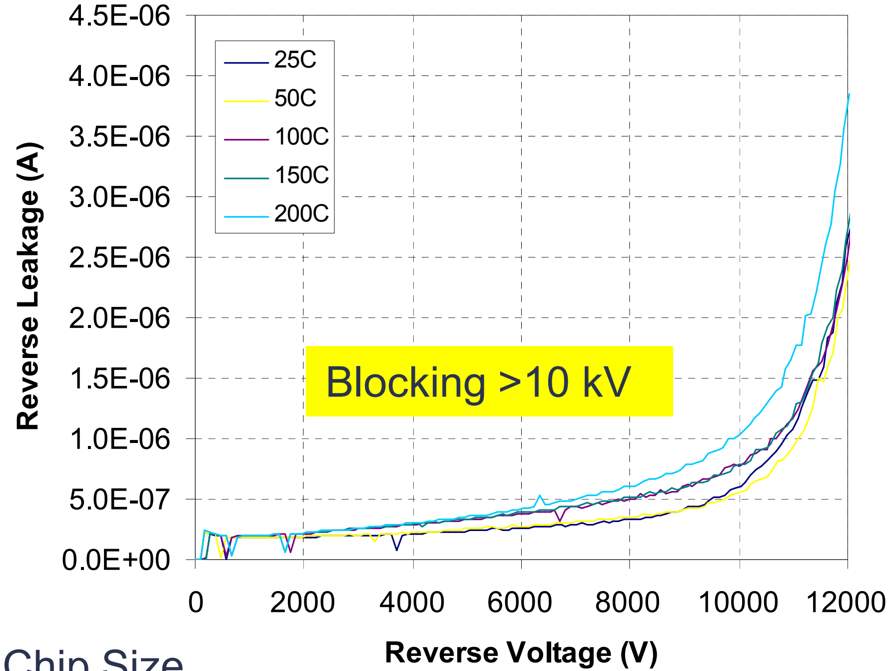


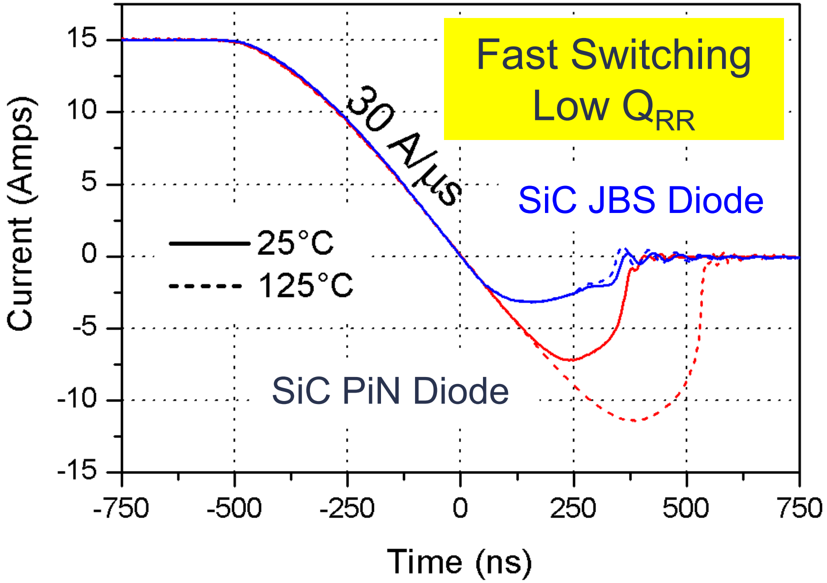

Courtesy of Penn State EOC
Prof. Joe Flemish & Mike Horgan

# Highest Voltage Schottky Diode

## 10 kV/10 A SiC Junction Barrier Schottky Diodes

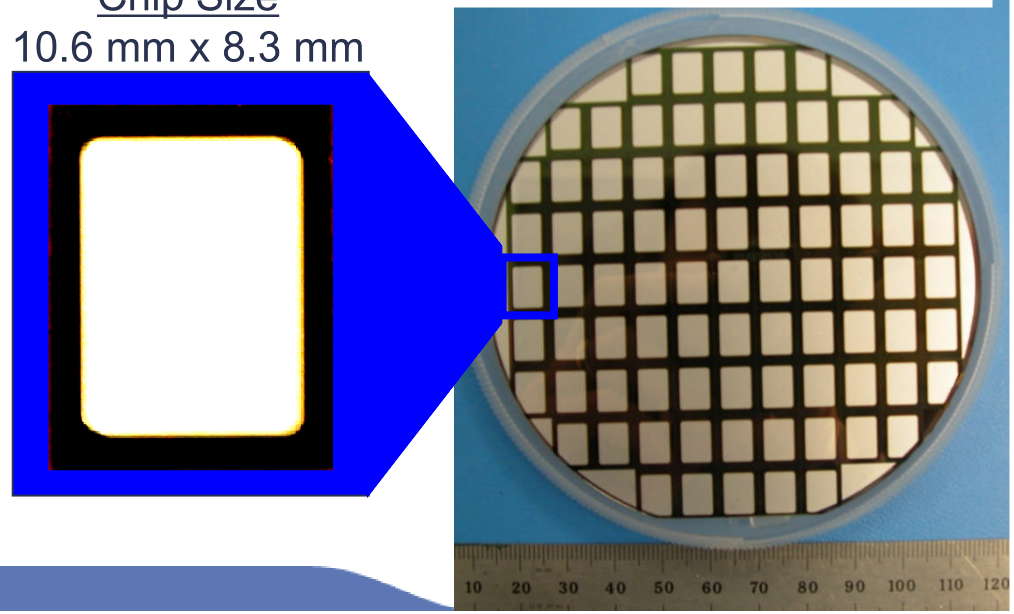


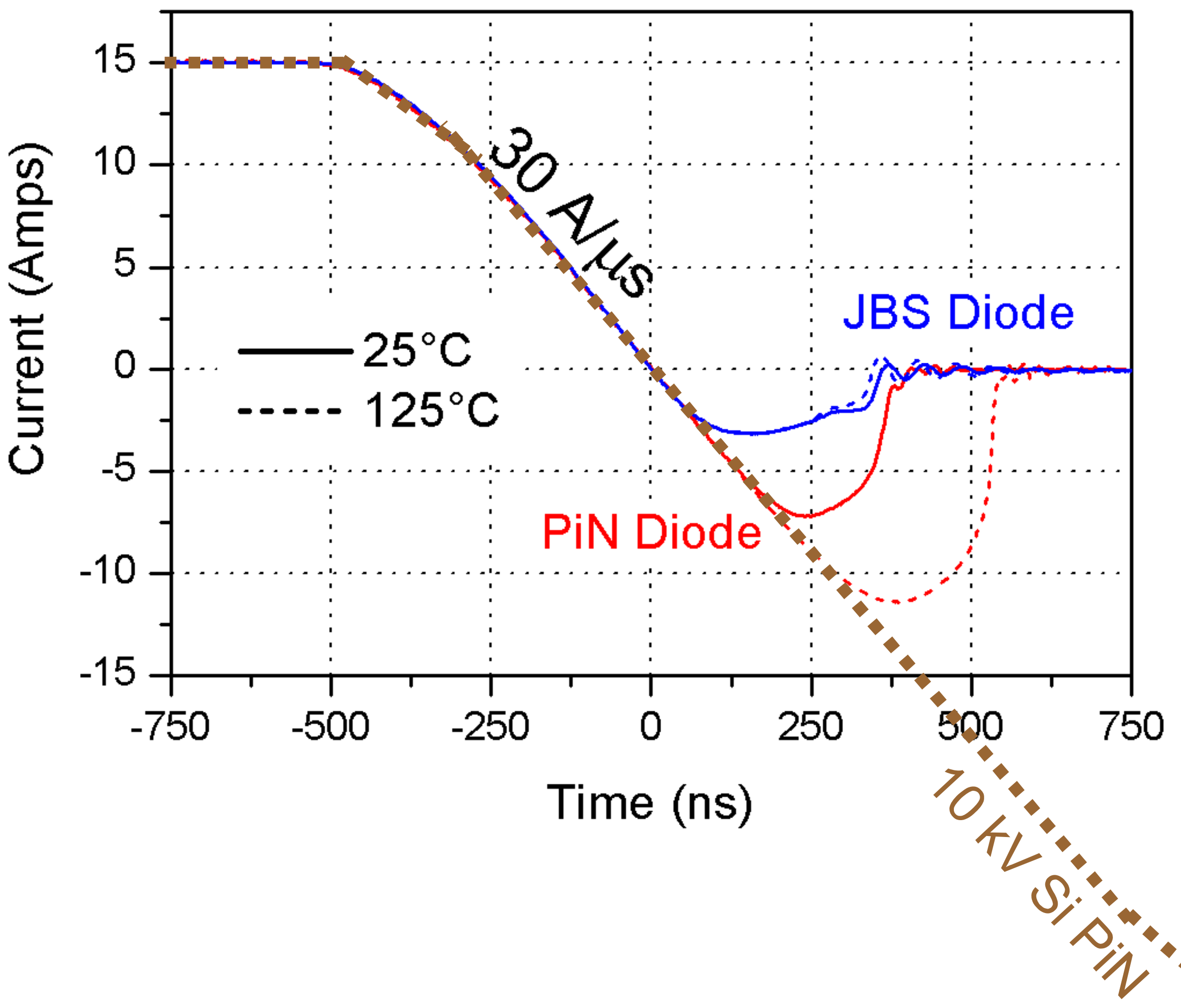

Chip Size

10.6 mm x 8.3 mm



# 10 kV/10 A SiC JBS Diode Switching

## Inductive Switching Characteristics



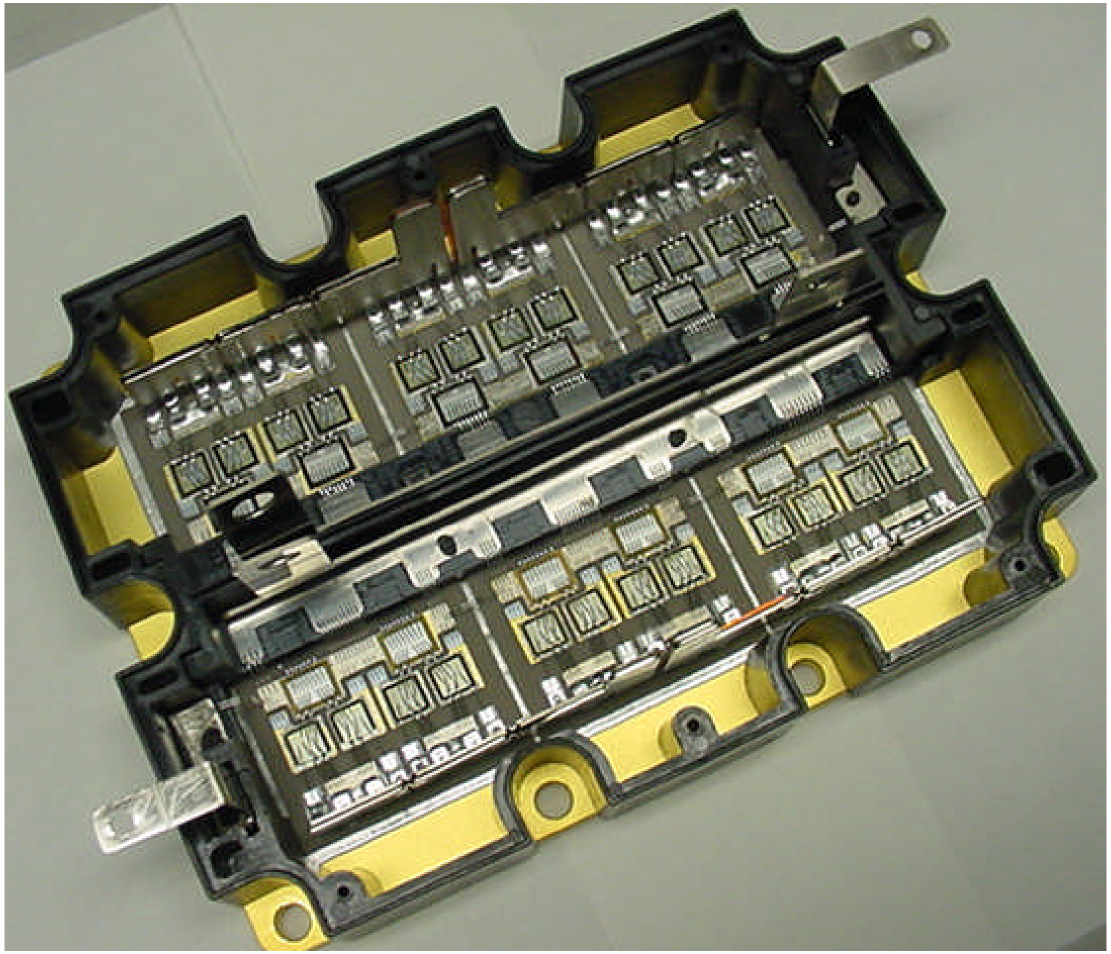

**JBS Diode**

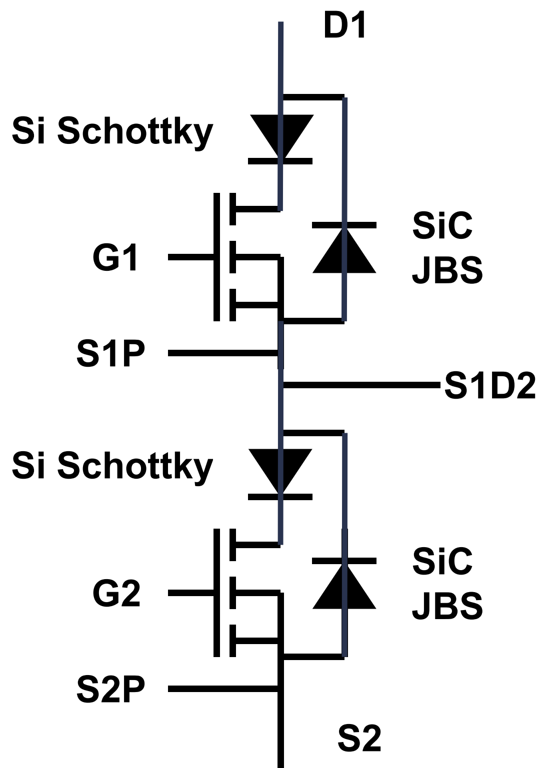
| | 25°C | 125°C |
|---|---|---|
| $t_{rr}$ | 365 ns | 350 ns |
| $I_{RM(rec)}$ | 3.15 A | 3.15 A |
| $Q_{rr}$ | 0.84 µC | 0.79 µC |

**PiN Diode**

| | 25°C | 125°C |
|---|---|---|
| $t_{rr}$ | 400 ns | 550 ns |
| $I_{RM(rec)}$ | 7.2 A | 11.4 A |
| $Q_{rr}$ | 1.8 µC | 4.0 µC |

# 10kV/120A SiC DMOSFET - JBS Diode
# Half H-Bridge Module Capable of 20 kHz Operation





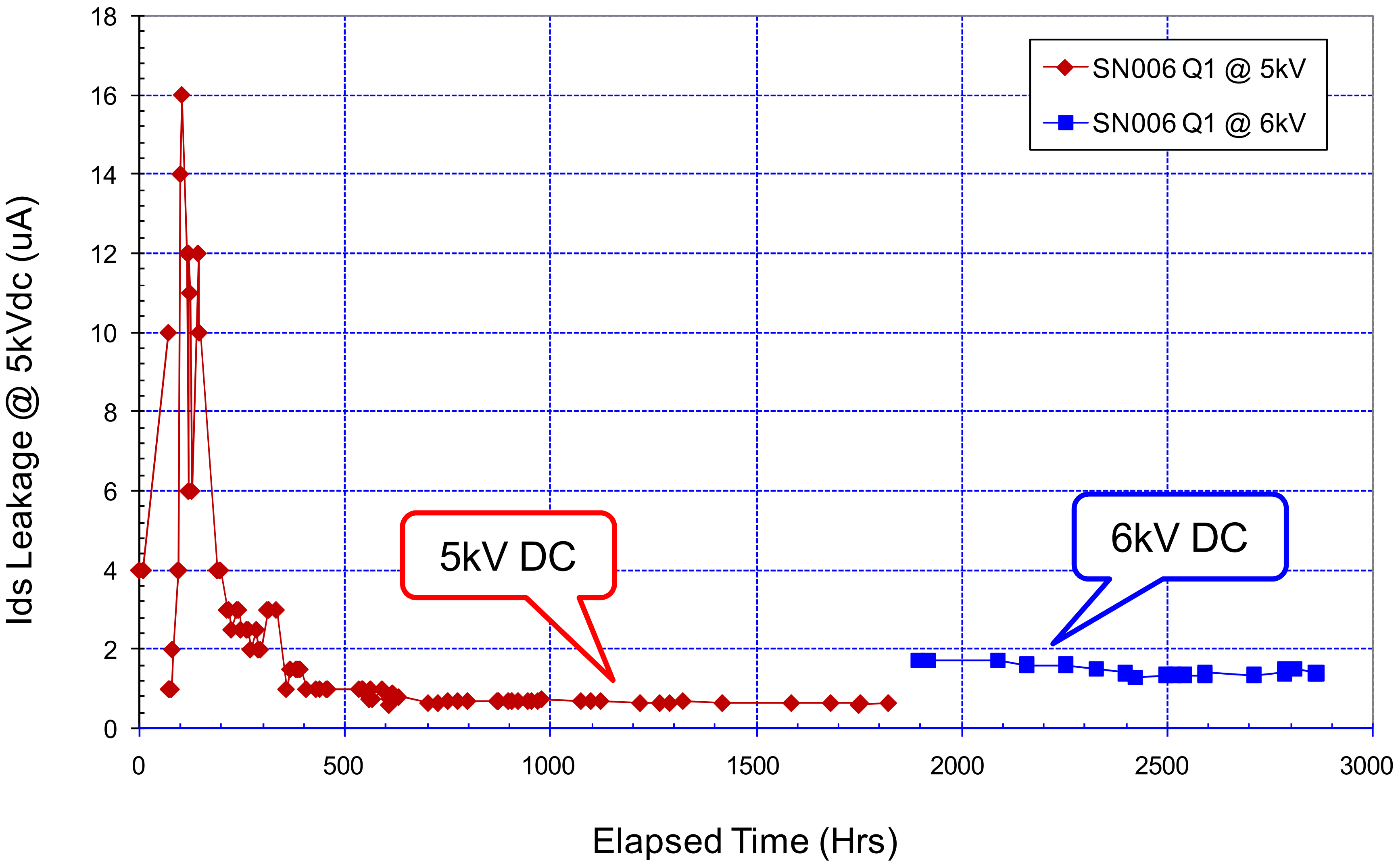

**Each switch comprised of 12 paralleled 10kV/10A SiC DMOSFETs**

**Each rectifier comprised of 6 paralleled 10kV/10A SiC JBS Diodes**

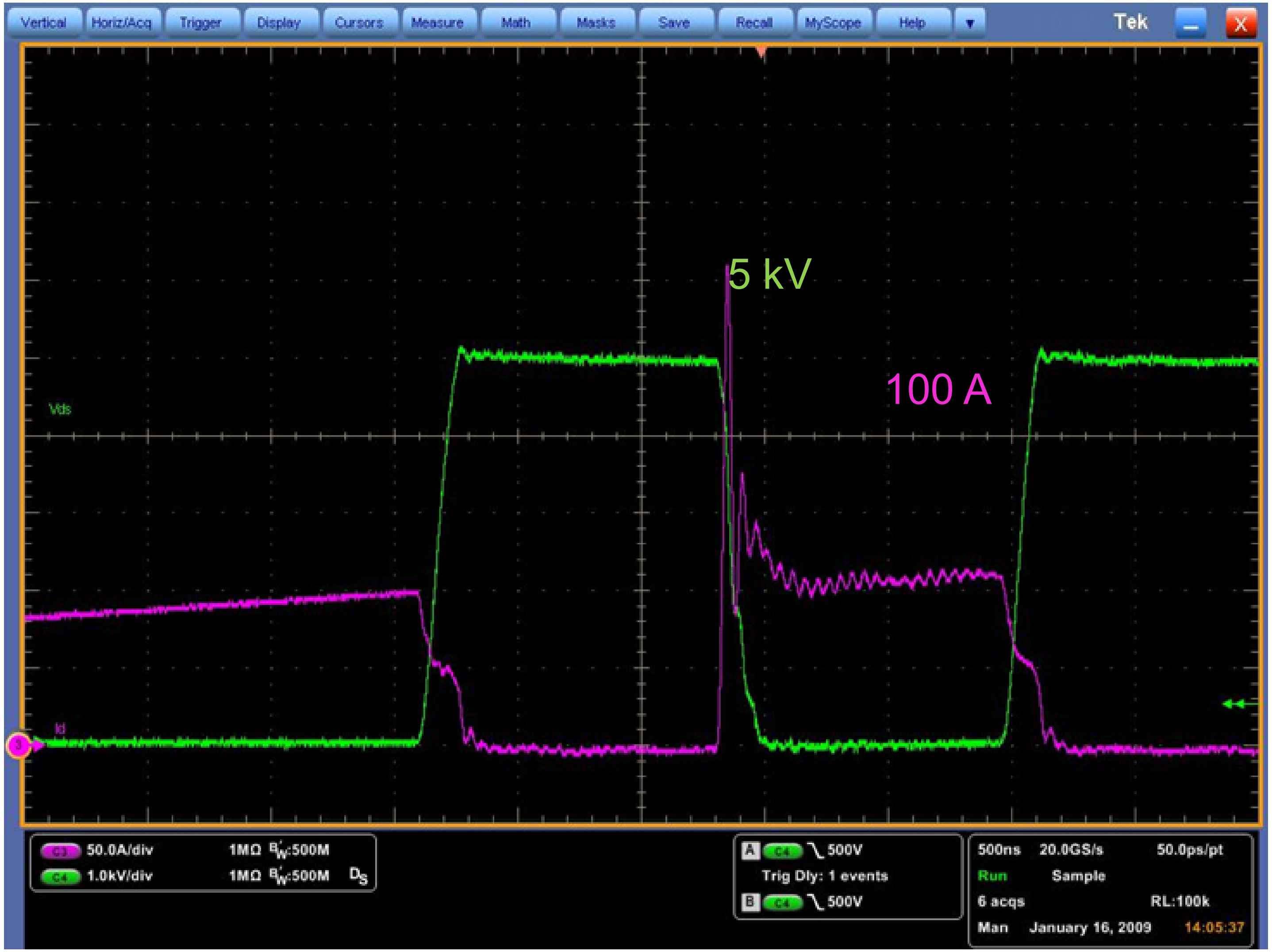
**Series Si Schottky to bypass SiC DMOSFET body diode**

# HPE III 10 kV/120 A Half H-Bridge Module

## Static HTRB Verifies High Voltage Capability



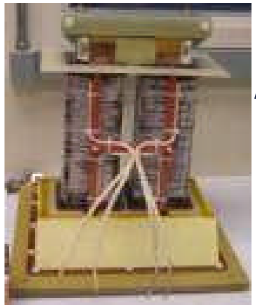
# 10 kV, 120 A SiC Half H-Bridge Module Switching Waveforms

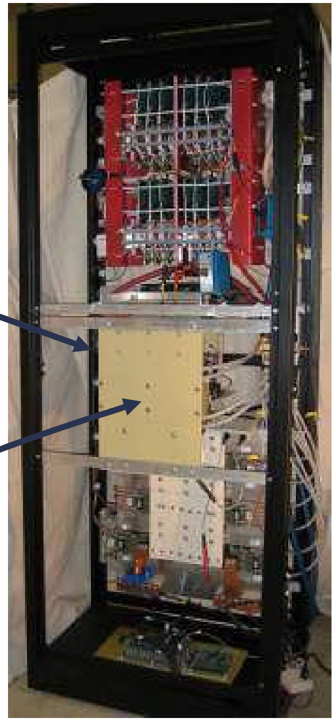


# 4 Stage - Single Phase (13.8 kV AC to 465/√3 V AC) SSPS Demonstratrated by GE and Tested at NSWC

One Stage AC-AC Building Block

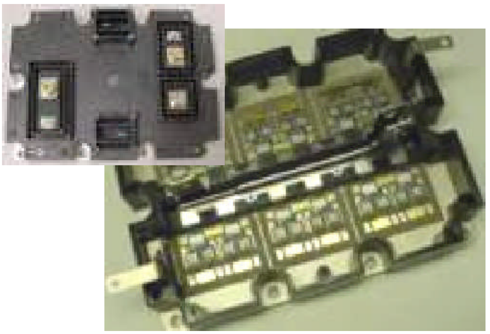
HF transformer





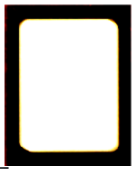
x 4

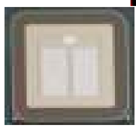
SSPS installed for testing at NSWC, Philadelphia (picture courtesy of NSWC & GE)



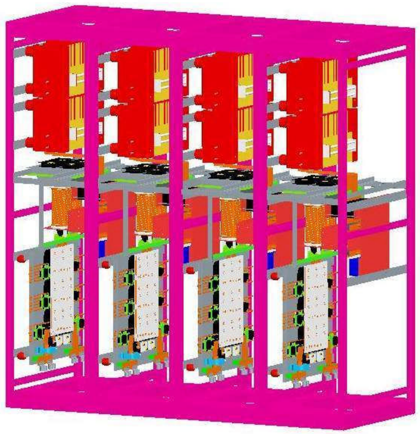
10 kV SiC Module

10 kV SiC JBS





10 kV SiC DMOSFET



Single Phase 1 MVA SSPS

Stacks tested to full power at GE

imagination at work

# Dramatic Reduction in SiC Module Size and Weight In 13.8 kV AC to 465/√3 V AC SSPS

## SiC 10 kV Modules are 9% of the Weight and 12% of the Volume of Si IGBT 13.5 kV Module

**SiC MOSFET Module**
**10 kV, 120amps**

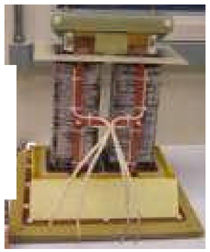
**Si IGBT Module**
**13.5 kV, 100amps**

# Dramatic Reduction in Transformer Size and Weight In 13.8 kV AC to 465/√3 V AC SSPS

**OTS Transformer**

**Los Alamos National Laboratory**
**High Frequency Transformer**

Los Alamos NATIONAL LABORATORY EST. 1943



Courtesy of Bill Reass

**250 kVA - 20 kHz transformer**
**16" high**
**75 lbs**

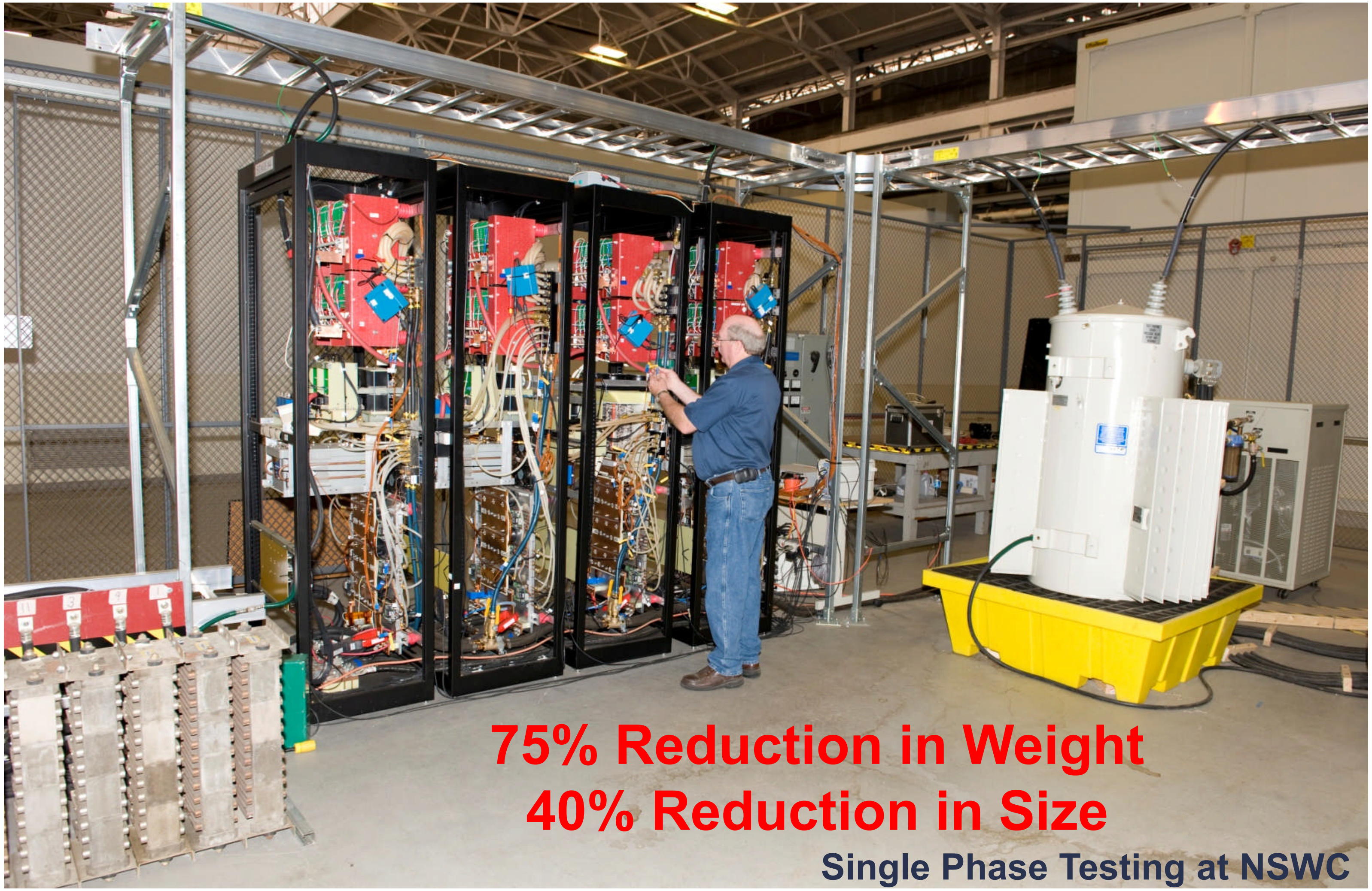
**330 kVA 60 Hz transformer**
**55" high**
**2700 lb**

imagination at work

CREE

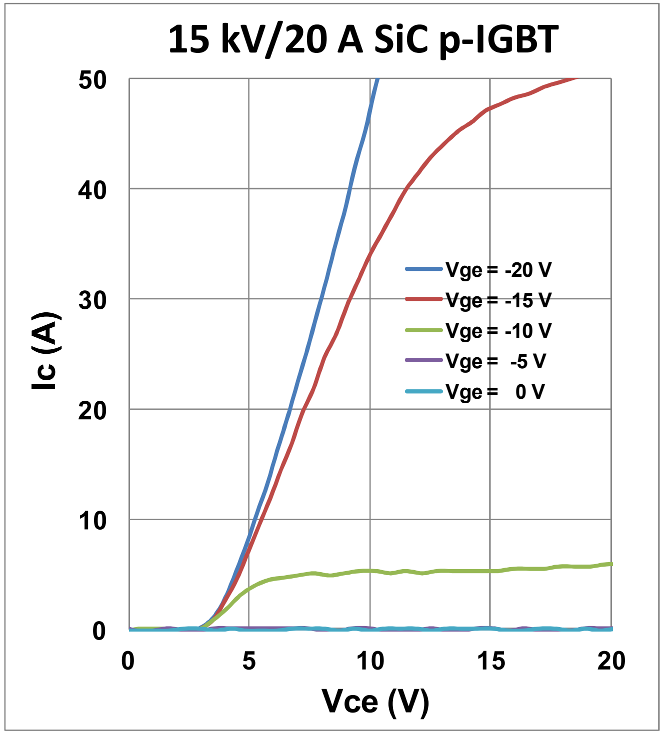
# 4 Stage - Single Phase (13.8 kV AC to 465/√3 V AC) SSPS Based on 10 kV/120 A SiC DMOSFET Modules

## Single Phase SSPS – Demonstrated 860 kVA Operation



# 15 kV/ 20 A SiC p-IGBT
## World's First 15 kV Semiconductor Switch

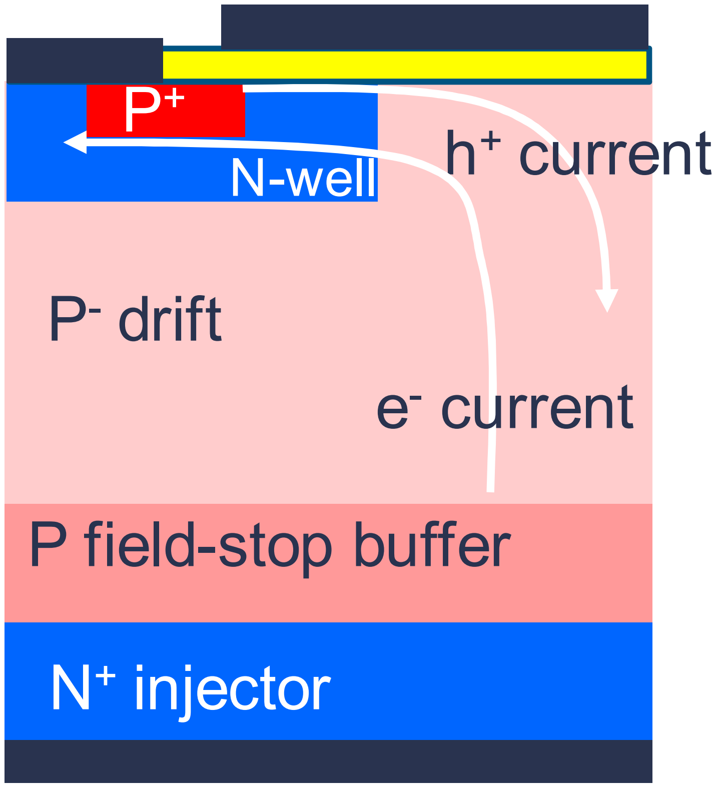
***SiC IGBT Power At Your Fingertips!***




- **15 kV/20 A SiC p-IGBT**
- $V_F$ = 6.5 V @ 20 A, $V_{GE}$ = 20V
- State-of-the-Art SiC p-IGBT Developed Under ARPA-E ADEPT Program

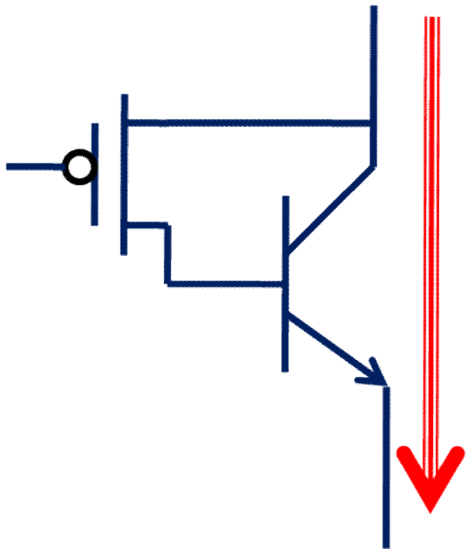
**15 kV SiC p-IGBT – World's Highest Voltage Semiconductor Switch**

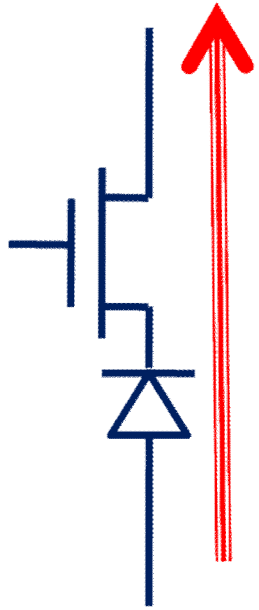
# SiC p-IGBT and SiC n-IGBT Operation




$I_e : I_h = \mu_e : \mu_h$

$= 10 : 1$ in 4H-SiC

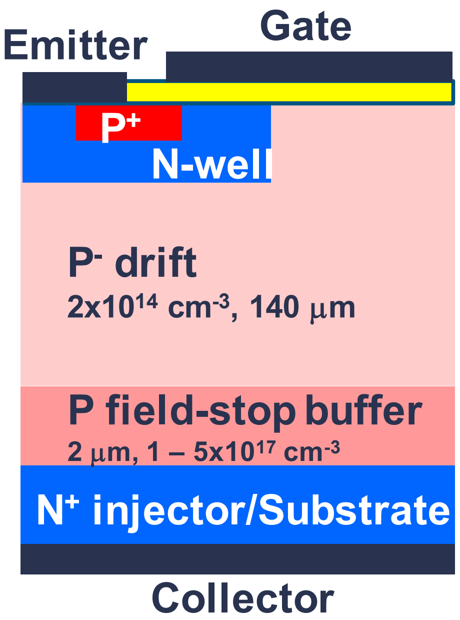




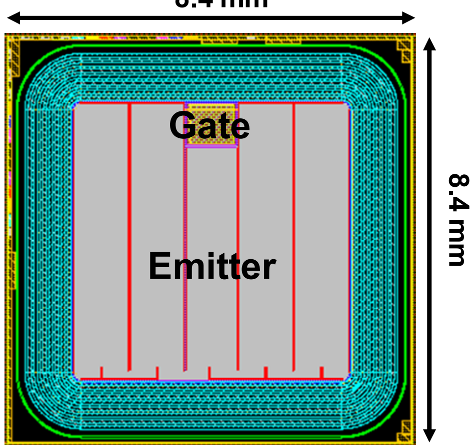
***P-IGBT:***
**Small PMOS driving a big NPN BJT**

***N-IGBT:***
**NMOS with cond. mod. drift layer**

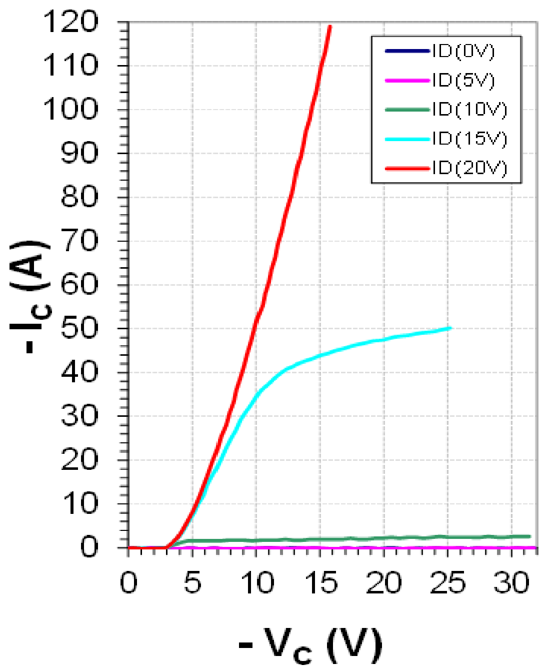
# 15kV/20A SiC p-IGBT
# DC Device Characteristics at 25ºC

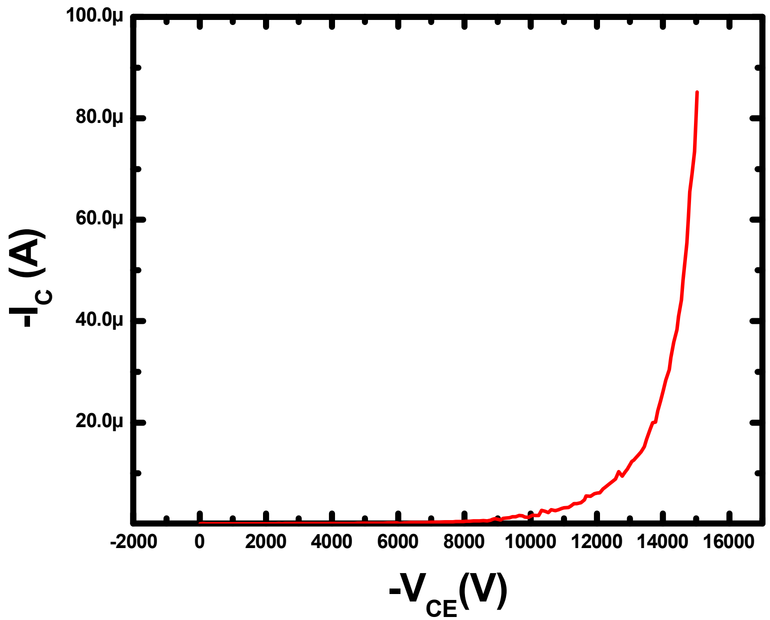



**SiC P-IGBT Structure**




**15 kV SiC p-IGBT - Highest Breakdown Voltage Ever Reported for a Semiconductor Switch!**



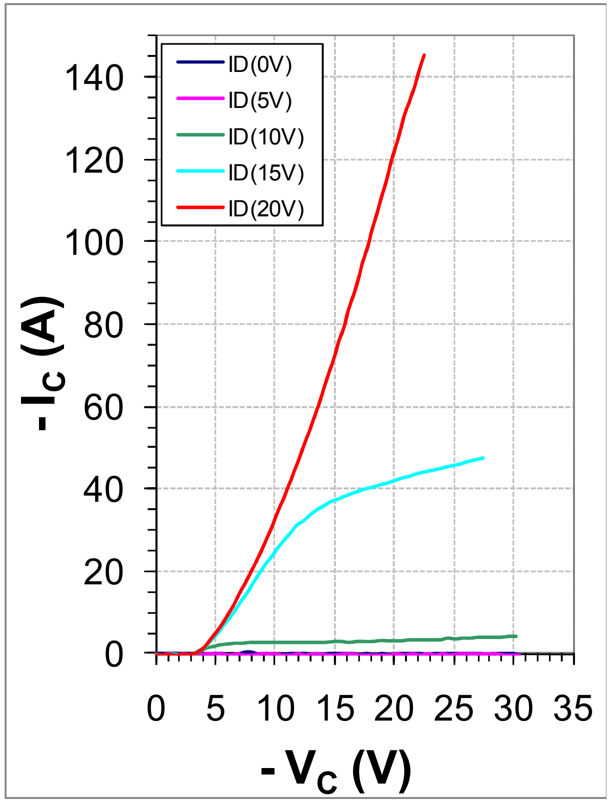

$V_F$ = 6.5 V @ 20 A, $V_{GE}$ = -20V

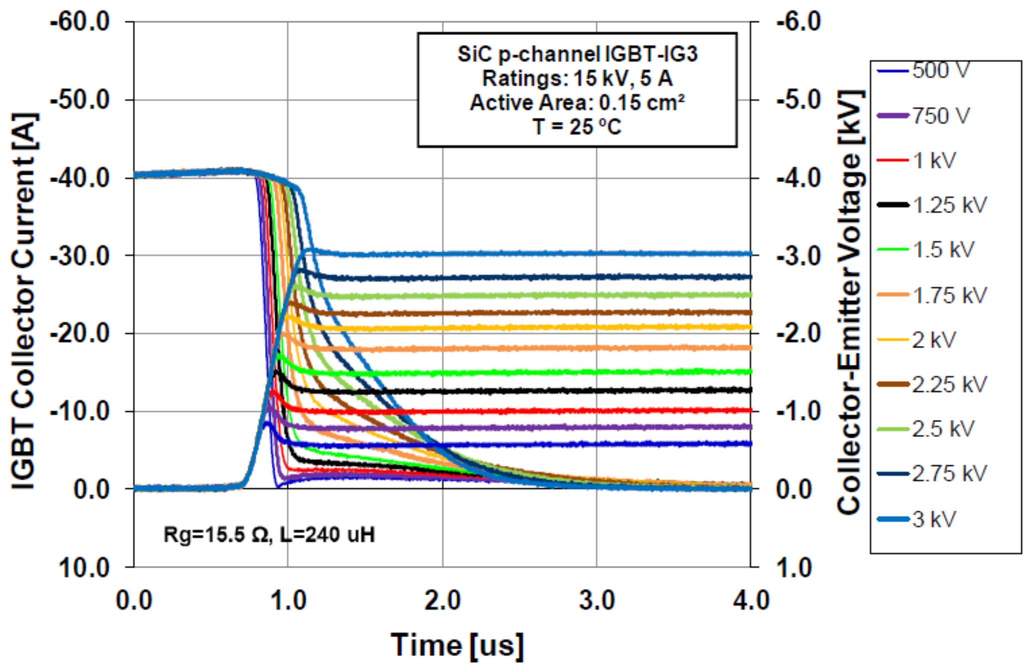
15 kV Blocking ($V_{GE}$=0V)

*Room Temperature Device Characteristics*

# No Latch-Up Observed In 15kV/10A SiC p-IGBT

Dr. A. Hefner, NIST

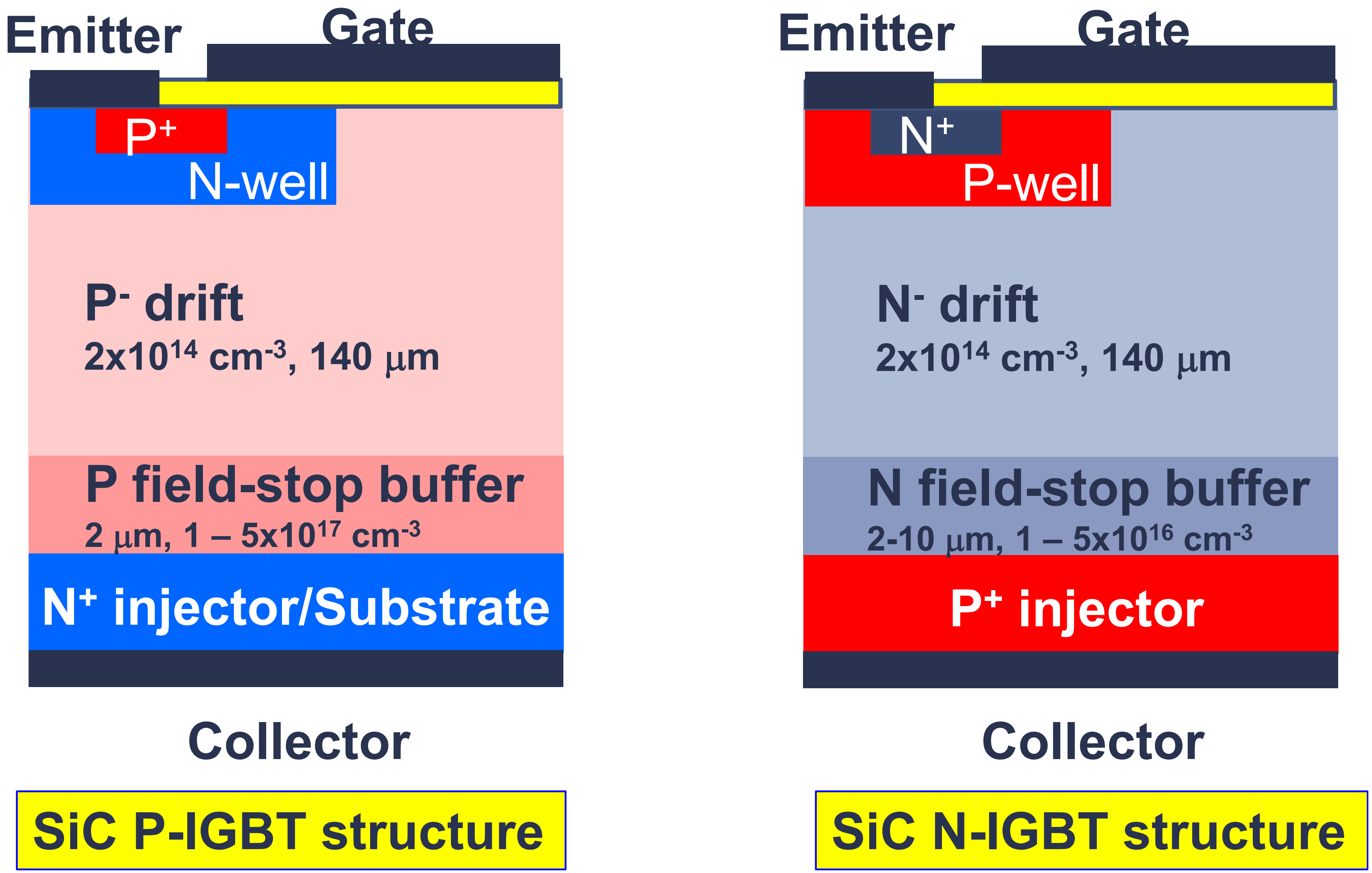



**No Static Latch-up @ $I_C$= 145 A @ 22.5 V**
**=> Current density: 906 A/cm²**
**=> Power density: 45 kW/cm²**

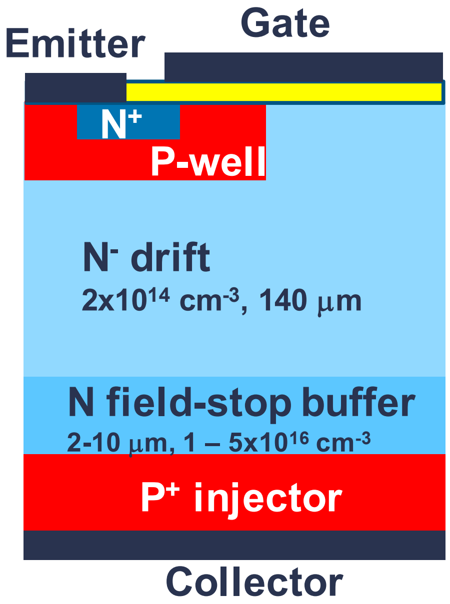
**No Dynamic Latch-up during turn-off transients: $I_C$ = -40A**

# 15 kV SiC p-IGBT and n-IGBT Device Structures
## (Based on SiC DMOSFETs)

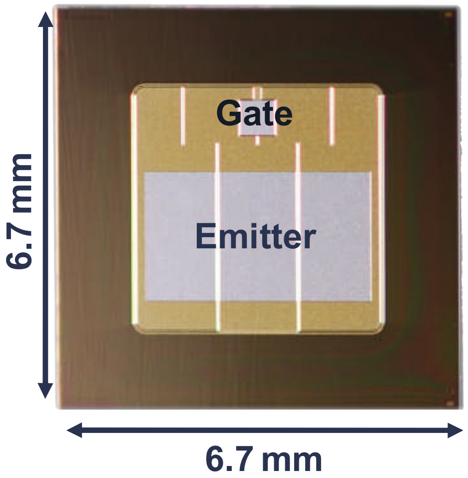


# 12.5kV/35A SiC n-IGBT
# DC Device Characteristics at 25°C

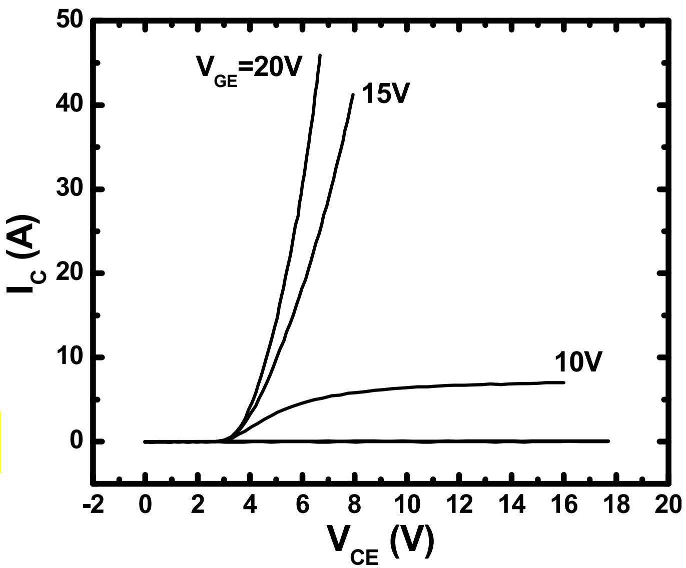
arpa·e

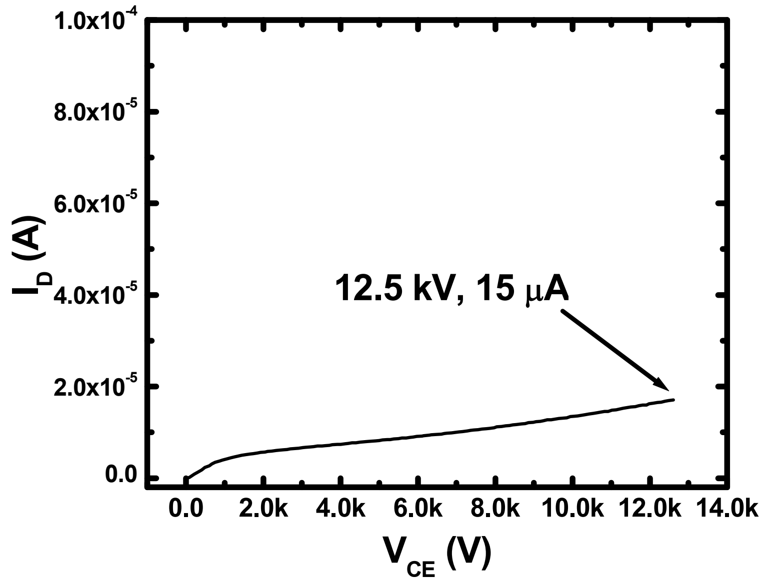



**SiC N-IGBT Structure**




***12.5 kV SiC n-IGBT With Specific On Resistance ($R_{on,sp}$) of Only 5.3 mΩ-cm² !***




$V_F$ = 4.1V @ 5 A, $V_{GE}$ = 20V
= 6.1 V @ 32 A (200 A/cm²)

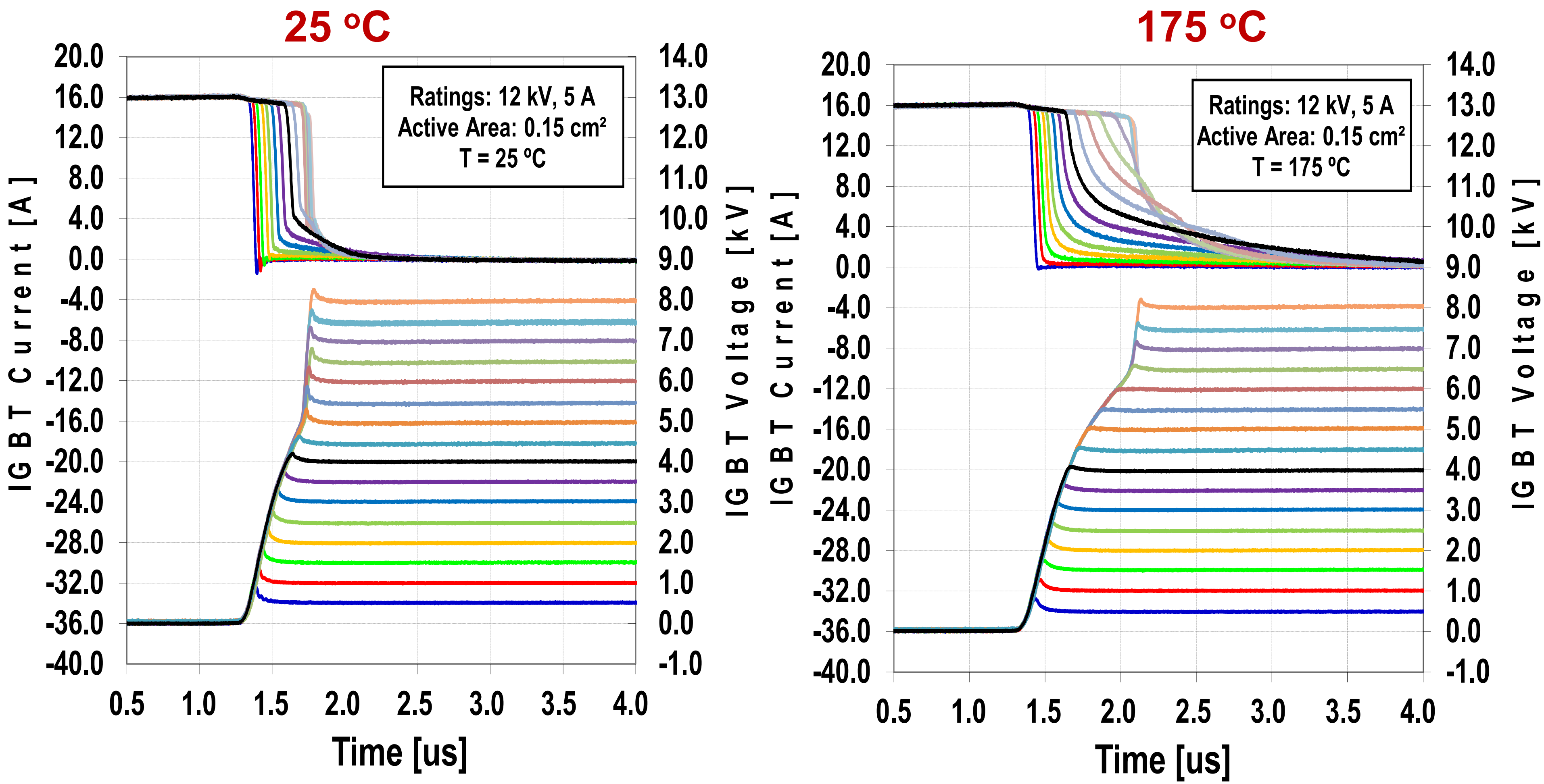
$R_{on,sp}$ = 5.3 mΩ-cm²
($V_{GE}$= 20V, $V_{CE}$= 6.1V)

**12.5 kV blocking**
**($V_{GE}$=0V)**

***Room Temperature Device Characteristics***

CREE

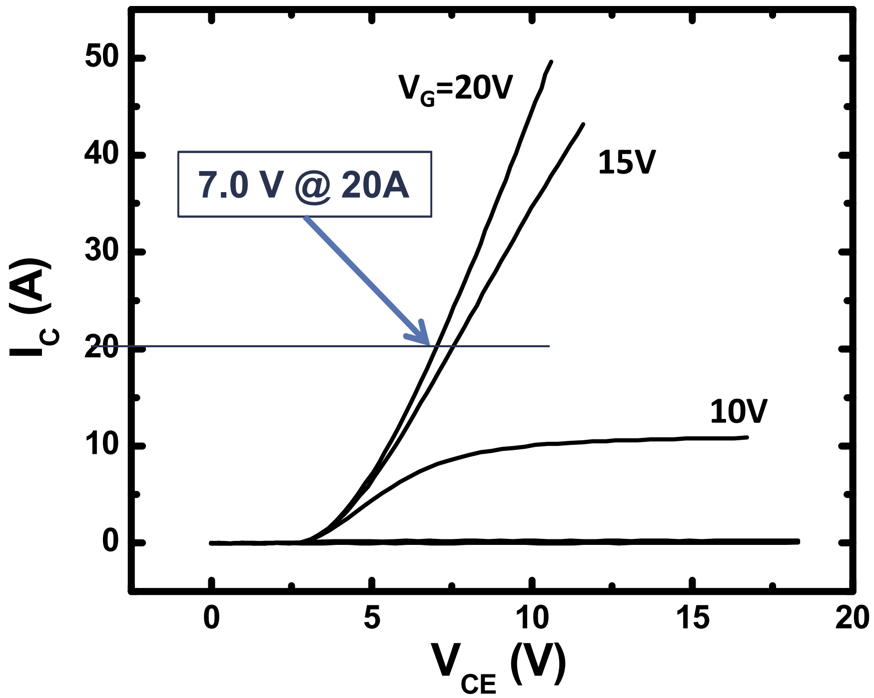
# 12.5kV SiC n-IGBT Turn-Off Switching Up to 8 kV at 25$^0$C and 175$^0$C

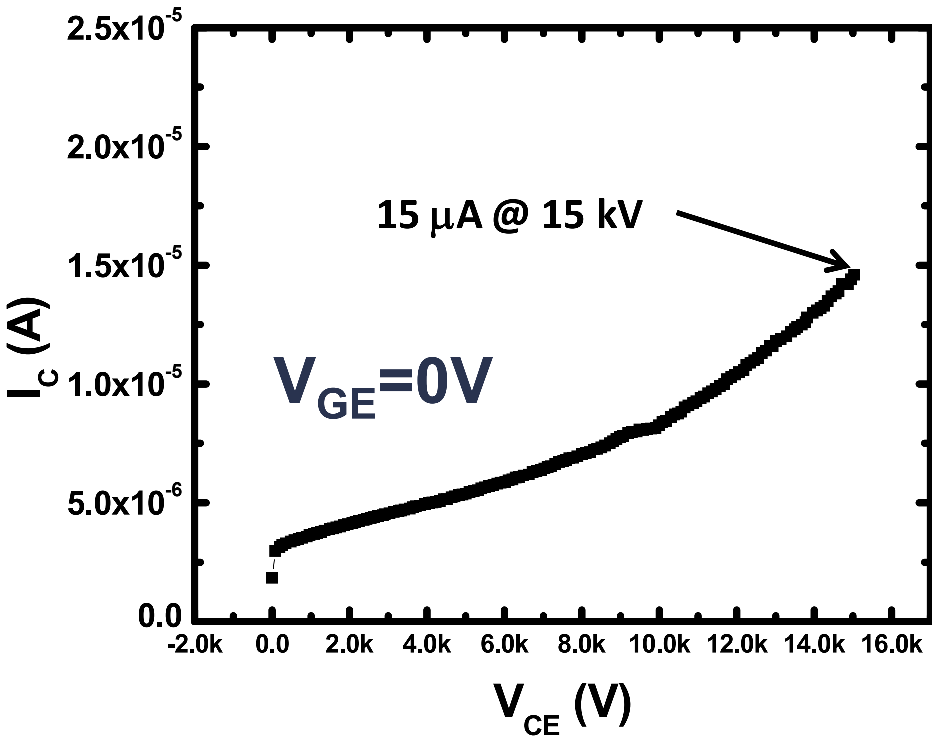



***Measurements by Al Hefner at NIST***

# 15 kV/20A SiC n-IGBT (Lot #4A) Successfully Demonstrated

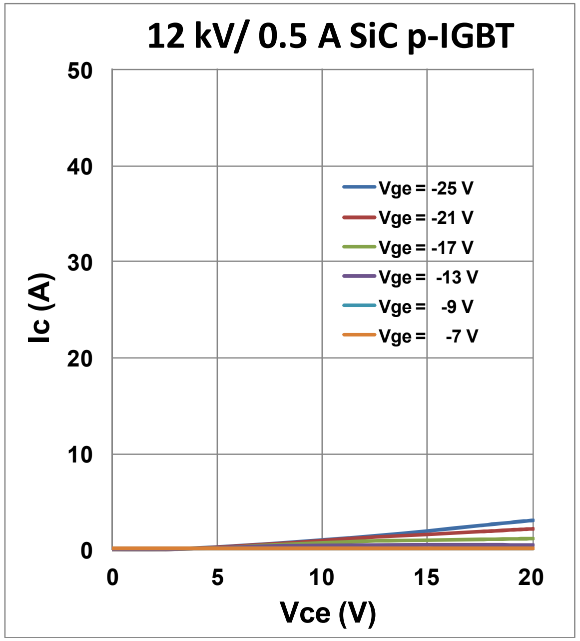
**15 kV/20 A SiC n-IGBT Lot #4A**
**Die Size: 8.4 mm x 8.4 mm / Active Area: 0.32 cm$^2$**

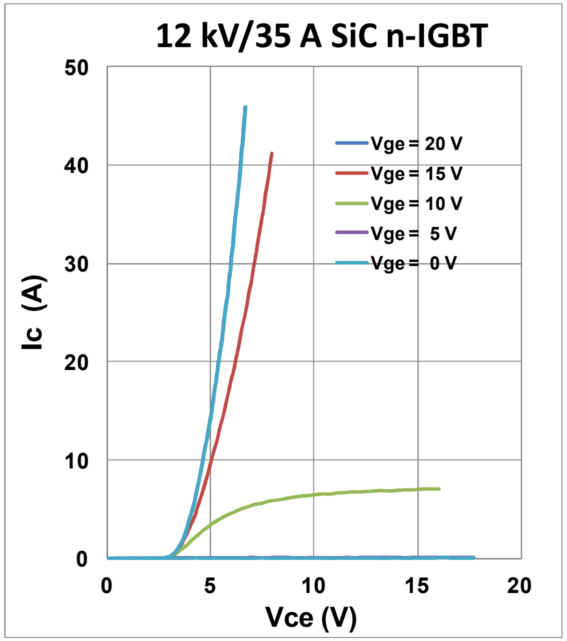


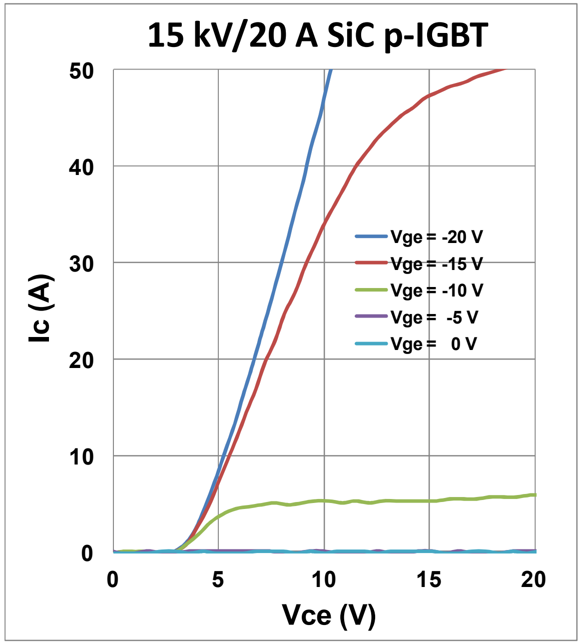




**Room temperature, on-wafer measurements**

# Dramatic Improvement in SiC IGBTs Under the ARPA-E ADEPT Program




- **12 kV/0.5 A SiC p-IGBT & n-IGBT**
- **$V_F$ = 6.5 V @ 0.5 A, $V_{GE}$ = 20V**
- **Previously Developed Under DARPA/ONR HPE Program**

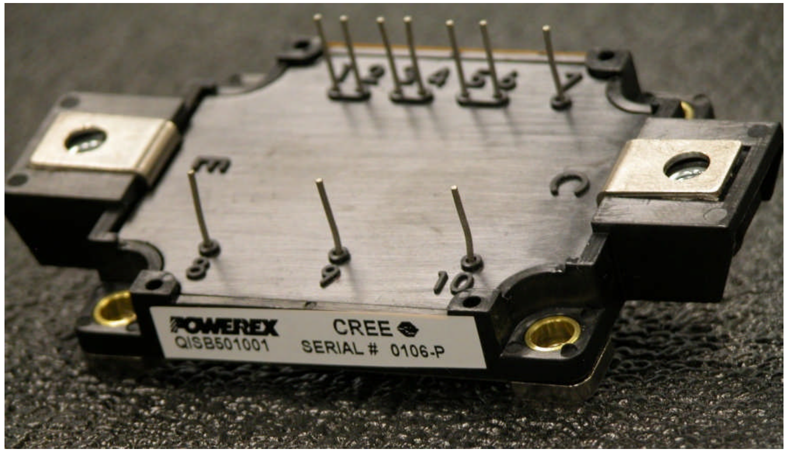
- **12.5 kV/35 A SiC n-IGBT**
- **$V_F$ = 6.5 V @ 35 A, $V_{GE}$ = 20V**
- **State-of-the-Art SiC n-IGBT Developed Under ARPA-E ADEPT Program**

- **15 kV/20 A SiC p-IGBT**
- **$V_F$ = 6.5 V @ 20 A, $V_{GE}$ = 20V**
- **State-of-the-Art SiC p-IGBT Developed Under ARPA-E ADEPT Program**

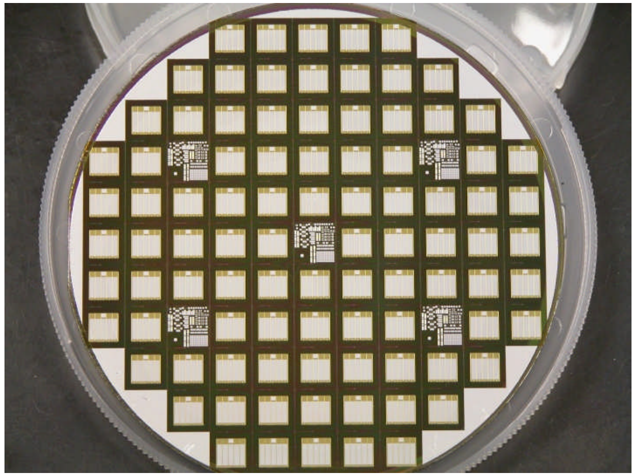
***SiC IGBT - Room Temperature Forward I-V Characteristics***

- **Dramatic Improvement in SiC IGBTs Under ARPA-E ADEPT Program**
- **Over 40x Increase in Current Rating of SiC n-IGBTs and SiC p-IGBTs**
- **15 kV SiC p-IGBT – Highest Voltage Semiconductor Switch Ever Developed**

# Highlights of SiC IGBT Development Under the ARPA-E ADEPT Program



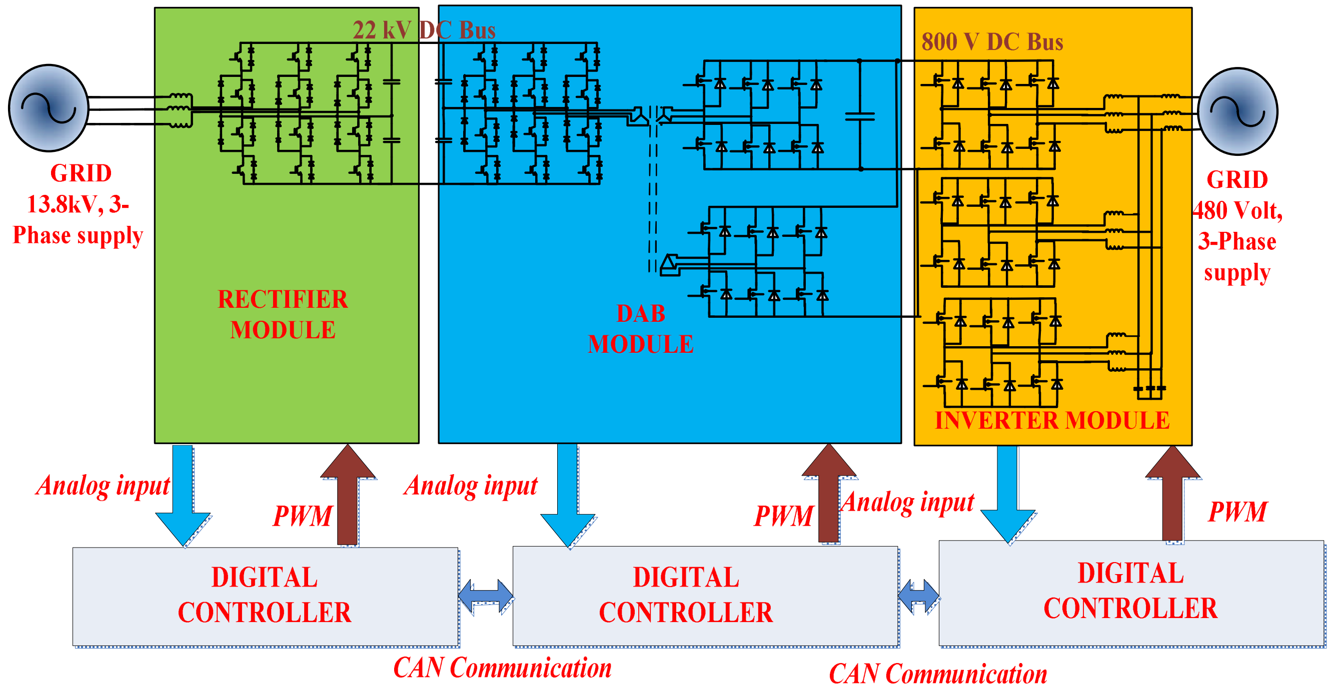

- 15 kV SiC IGBT Switch Module – World's Highest Voltage Semiconductor Switch



- 15 kV/10 A SiC p-IGBTs Fabricated On 100 mm 4HN-SiC Wafer

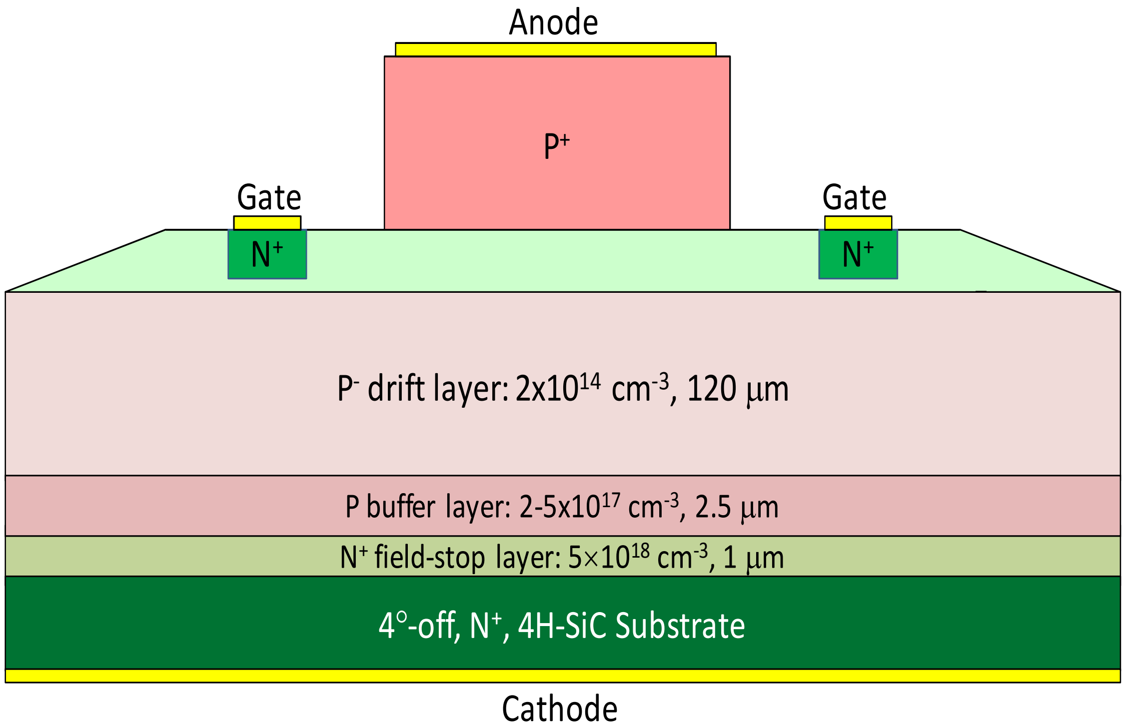
- Developed **15 kV SiC IGBT – World's Highest Voltage Semiconductor Switch**
  - Over 2x Higher Than 6.5 kV SiC IGBT
- **SiC IGBTs** Capable of Switching Over **20x Faster** Than Si IGBT
- Higher Voltage and Switching Speed of **SiC IGBTs** Enables a **3x to 5x Reduction in Size and Weight** of Solid State Transformer (TIPS)
- **SiC IGBTs** Result in a **3x to 4x Reduction in Losses** for Solid State Transformer (TIPS)

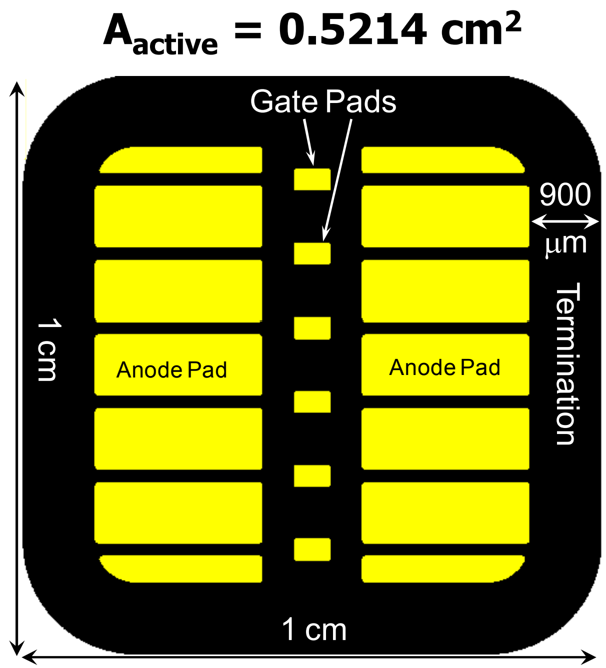
# NCSU Developing TIPS Based Upon 15 kV SiC IGBTs




- **Develop 13.8 kV to 480 V Solid State Distribution Transformer With Dramatically Reduced Weight and Size**
- **TIPS Functions as VAR Compensator On Both HV and LV Side.**
- **15 kV SiC IGBT Power Switches on HV Side and 1.2 kV SiC MOSFET Power Switches on LV Side**
- **High Frequency Link Nanocrystalline Transformer Provides Magnetic Isolation**

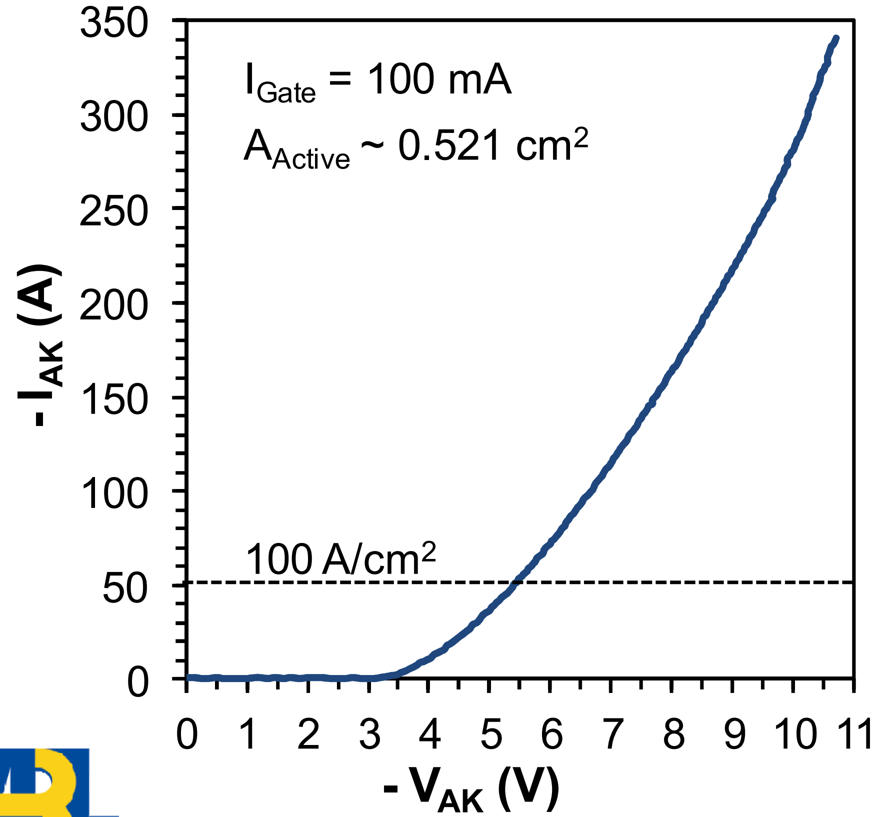
# 11526DCC1: 15 kV, 1 $cm^2$, SiC p-SGTO

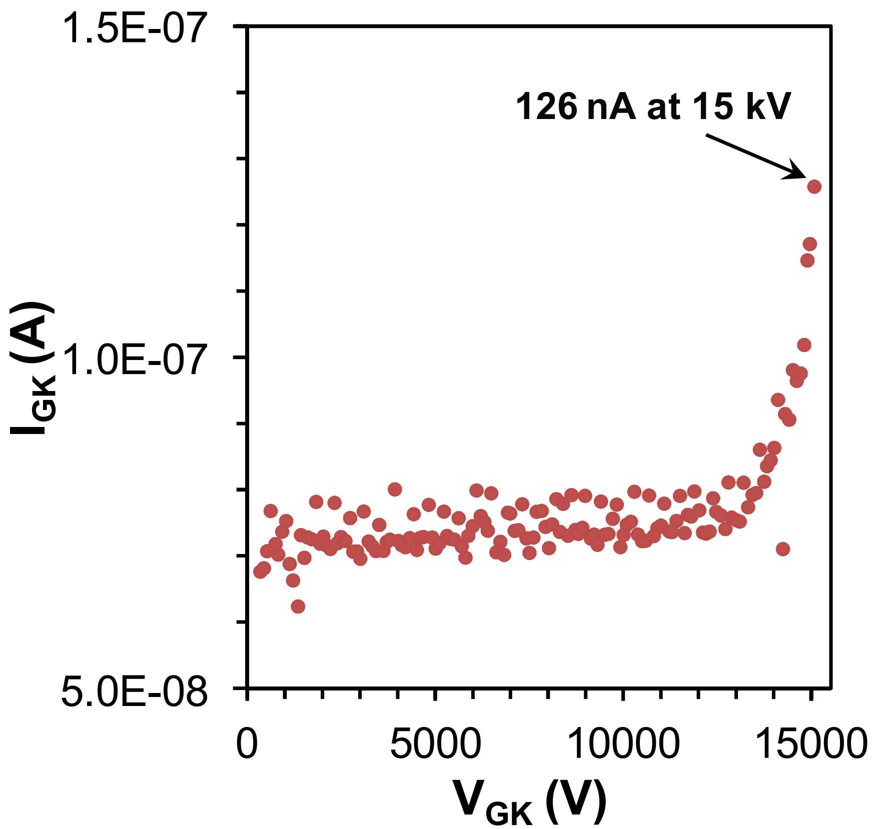


# 11526DCC1: DC Characteristics of SiC p-SGTO

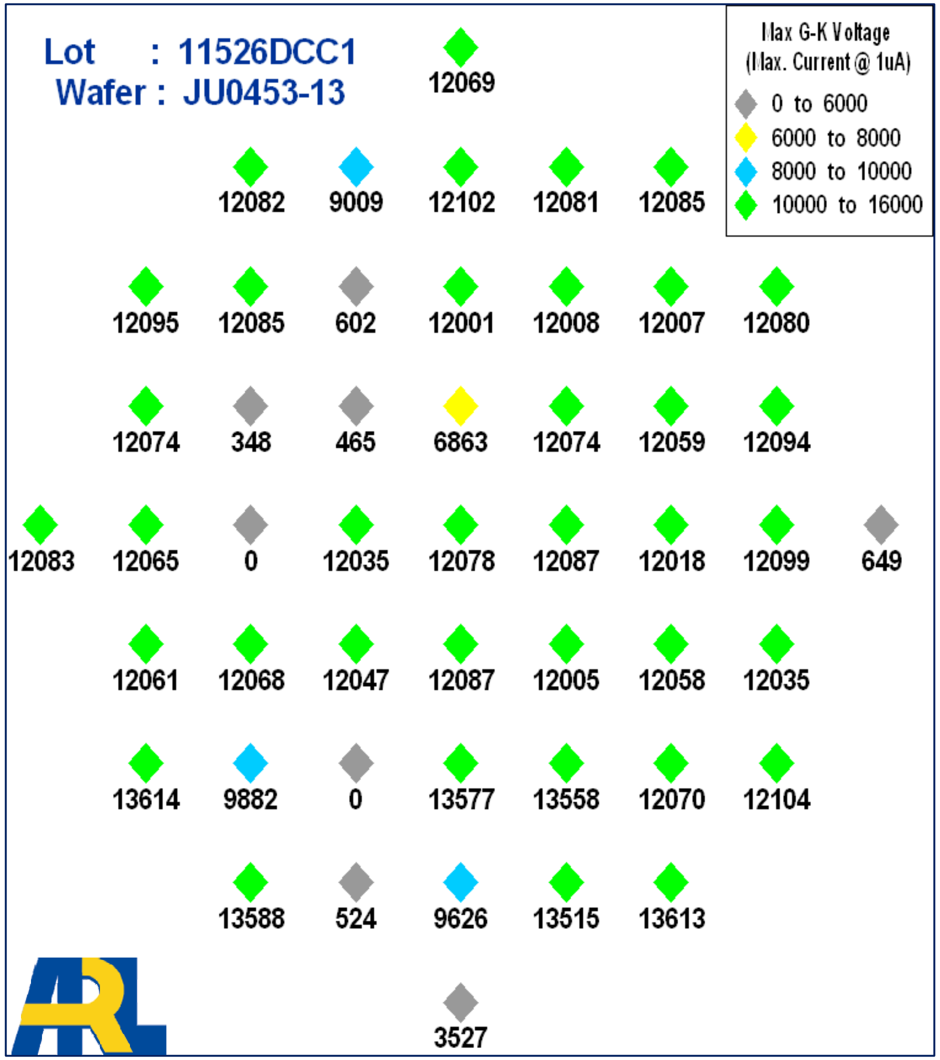
- $V_f$ (100 A/cm²) = 5.47 V, $V_f$ (650 A/cm²) = 10.68 V
- Avg. $R_{ON,diff}$ = 9.5 mΩ·cm² at 100~650 A/cm²
- Avg. $R_{ON,diff}$ = 5.99 mΩ·cm² at 600~650 A/cm²



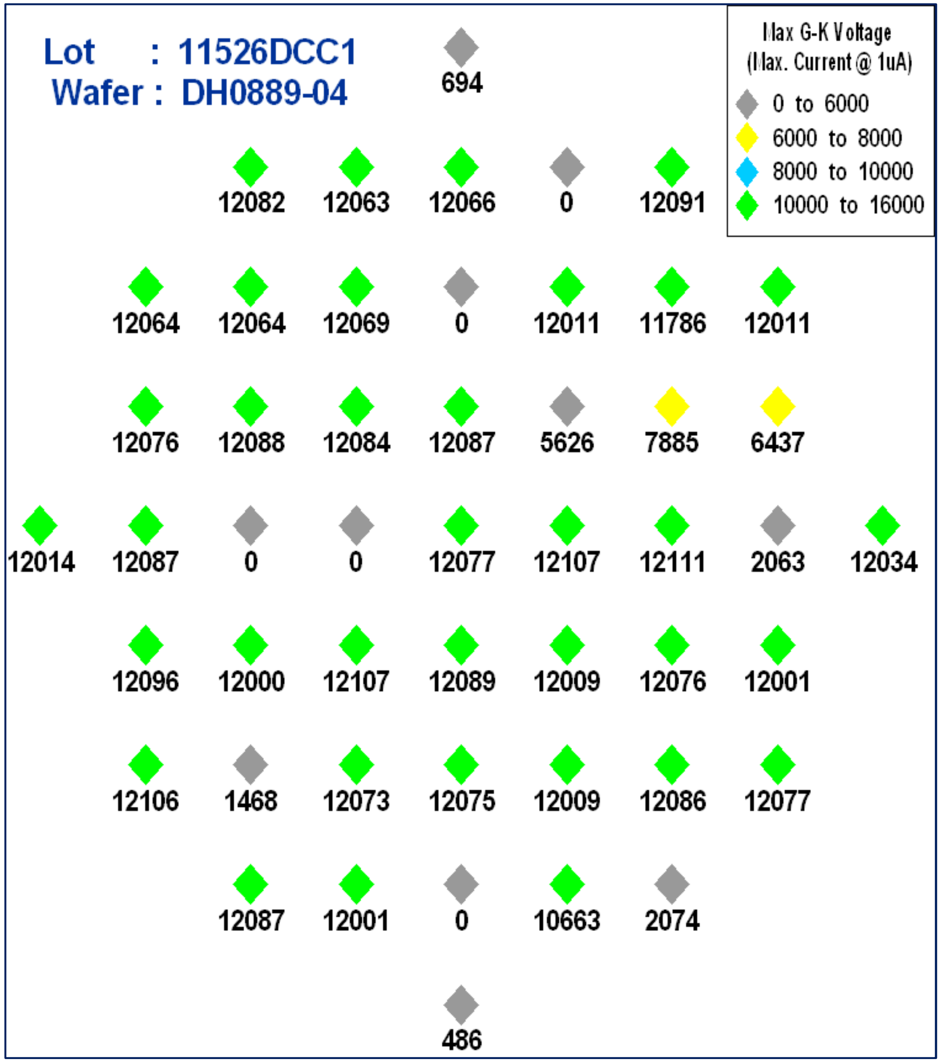



# 11526DCC1: 1 cm$^2$, SiC p-SGTO: on-wafer BV maps

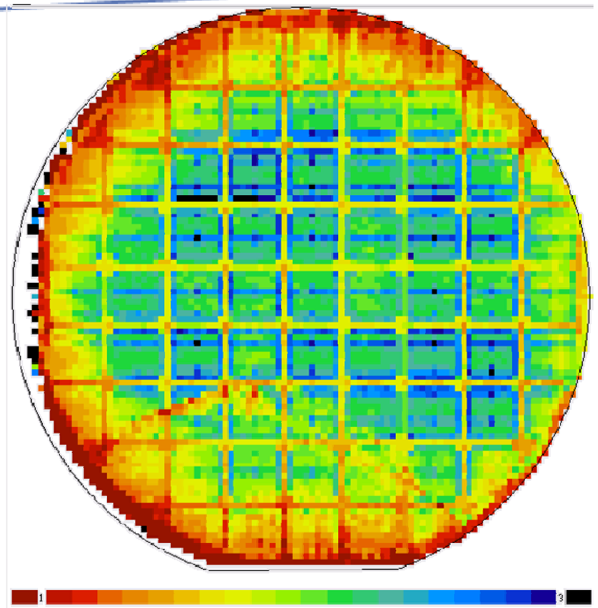
**12 kV @ ≤ 1 μA yield: 77.6% (38/49)**



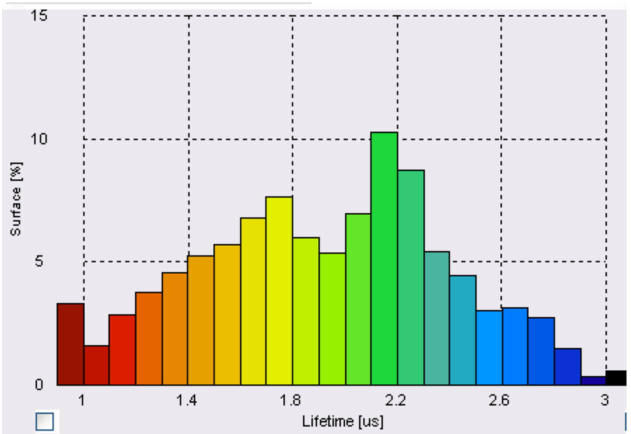

**12 kV @ ≤ 1 μA yield: 73.5% (36/49)**



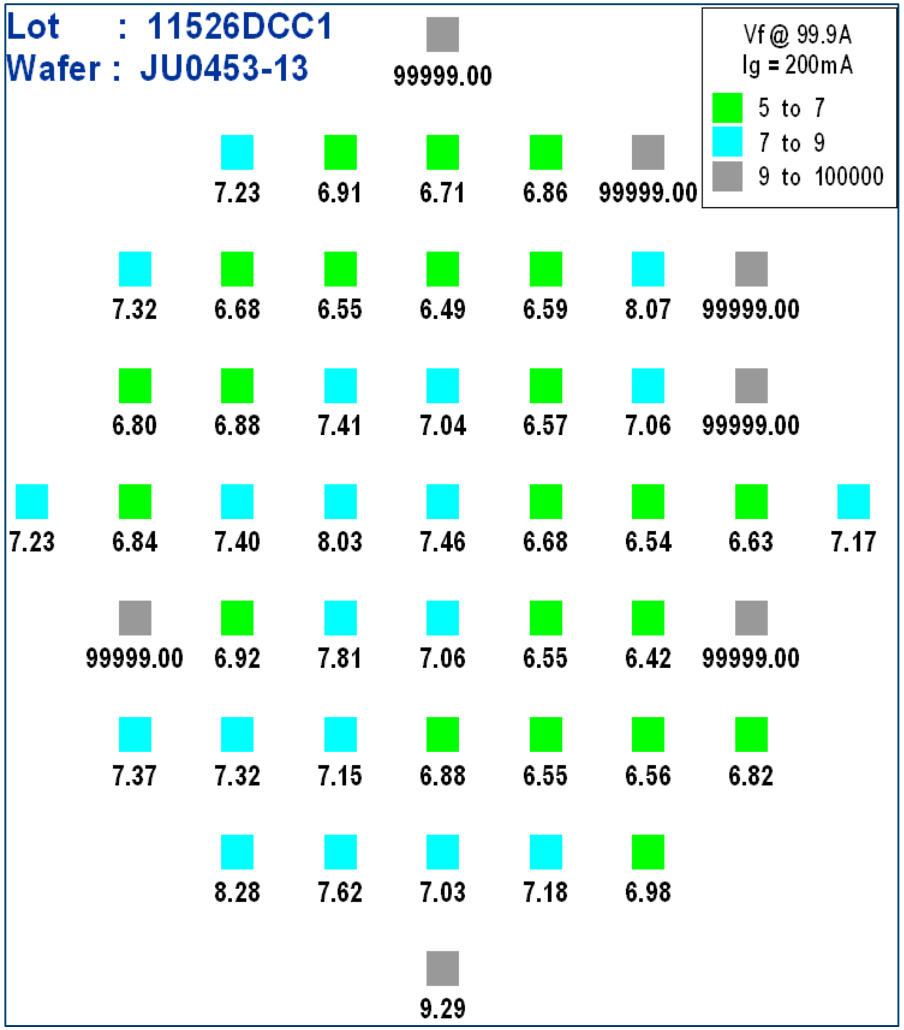
# 11526DCC1: 1 $cm^2$, SiC p-SGTO: on-wafer $V_f$ map



| | | | |
|---|---|---|---|
| Average: | 1.93 | Minimum: | 0.36 |
| Median: | 1.95 | Maximum: | 17.677 |
| Deviation: | 33.109 | | |




**Avg. $V_f$ = 6.98 V, Median $V_f$ = 7.09 V**



# Acknowledgements

NIST — Dr. Allen Hefner

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PennState EOC Electro-Optics Center — Prof. Joe Flemish, Mr. Mike Horgan

GE imagination at work — Ravi Raju, Michael Schutten, Bob Steigerwald

NC STATE UNIVERSITY — Dr. Subhashish Bhattacharya

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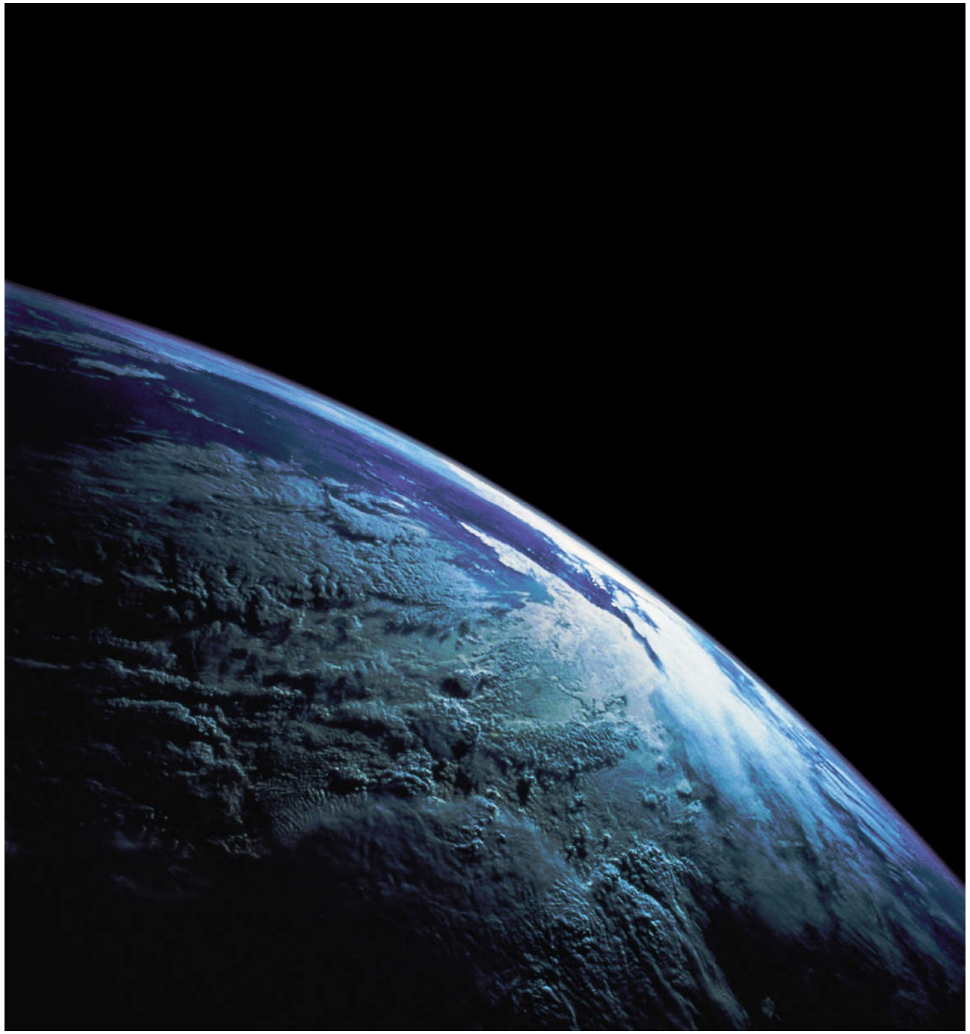
arpa·e — Rajeev Ram



CREE



# Cree SiC Power

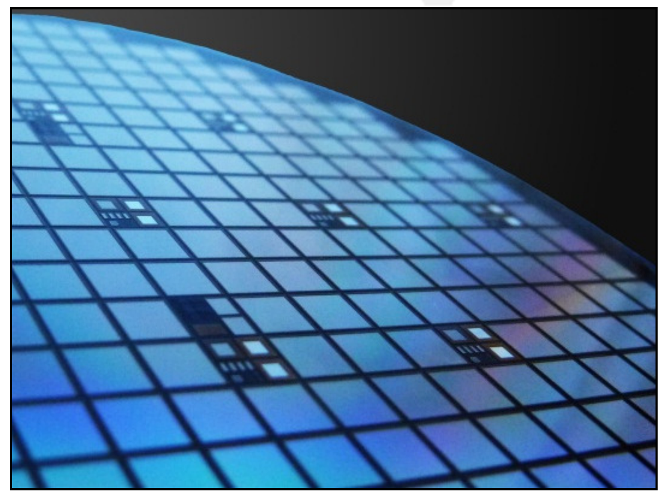
- ***The material difference.***

David

Sheridan

# Silicon Carbide Device Update

**David Sheridan**
VP Technology Development



**High Megawatt Power Conditioning System Workshop**

david.sheridan@semisouth.com

www.semisouth.com

SemiSouth

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# SiC Advantages

| Material property | Si | 4H-SiC | GaN |
|---|---|---|---|
| Bandgap | 1.12 eV | 3.25 eV | 3.4 eV |
| Breakdown field | 0.25 MV/cm | ~3 MV/cm | ~3 MV/cm |
| Thermal conductivity | 1.5 W/cm•K | 4.9 W/cm•K | 1.3 W/cm•K |
| Electron mobility | 1200 $cm^2/V \cdot s$ | 800 $cm^2/V \cdot s$ | 900 $cm^2/V \cdot s$ |
| Dielectric constant | 11.7 | 9.7 | 9 |

- Silicon carbide is an ideal power semiconductor material
- Most mature "wide bandgap" power semiconductor material
- Electrical breakdown strength ~ 10X higher than Si
- Commercial substrates available since 1991 –
  - ✓ **now at 100 mm dia; 150 mm dia soon**
- *Defects up to 1,000 times less than GaN*
- *Thermal conductivity ~ 3X greater than Si or GaN*

SemiSouth

# SemiSouth Introduction

## SemiSouth → SiC Power Semi Technology Leader

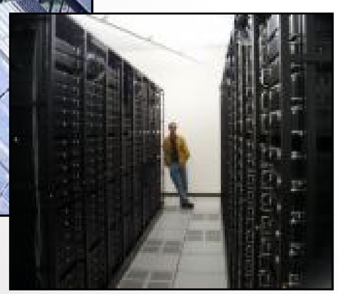
→ **1200 V – 1700 V Trench “normally – off” JFETs**

→ **650 V, 1200V – 1700 V Trench “normally – on” JFETs**

→ **1200 V Schottky Diodes**

***SemiSouth silicon carbide trench technology offers higher efficiency, greater power density & higher reliability than comparable silicon-based devices***

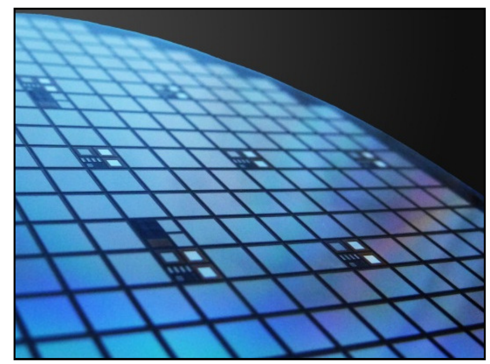
Solar



Servers

HEV

Wind



SiC Wafer

# SemiSouth SemiSouth VJFET Technology

- **Why the SiC Trench JFET?**
  - **Cost**
  - **3-10 X smaller** die size
  - Up to **50% fewer manufacturing steps**

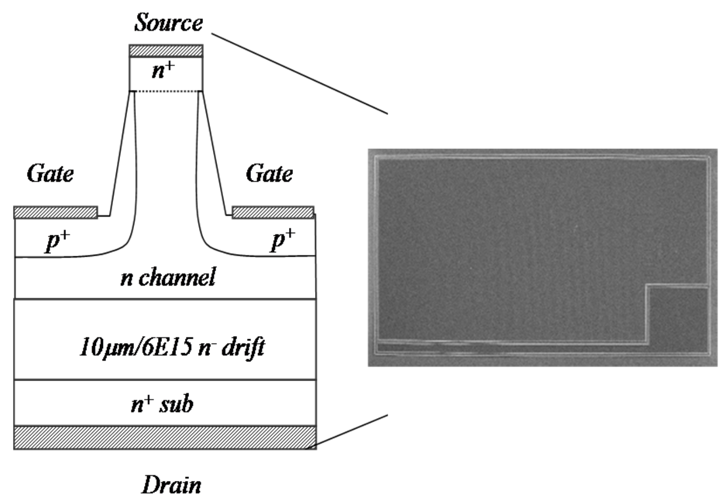
**Performance**

- **5-10X lower** switching energies
- **Normally-on or off** (industry first and only)
- Enables high-frequency ***and*** high-efficiency
- Industry best on-resistance per unit area

**Reliability**

- Rugged structure for SiC JFET switch
- Over 1,000 hour HTRB
- No known degradation issues
- Robust operating range

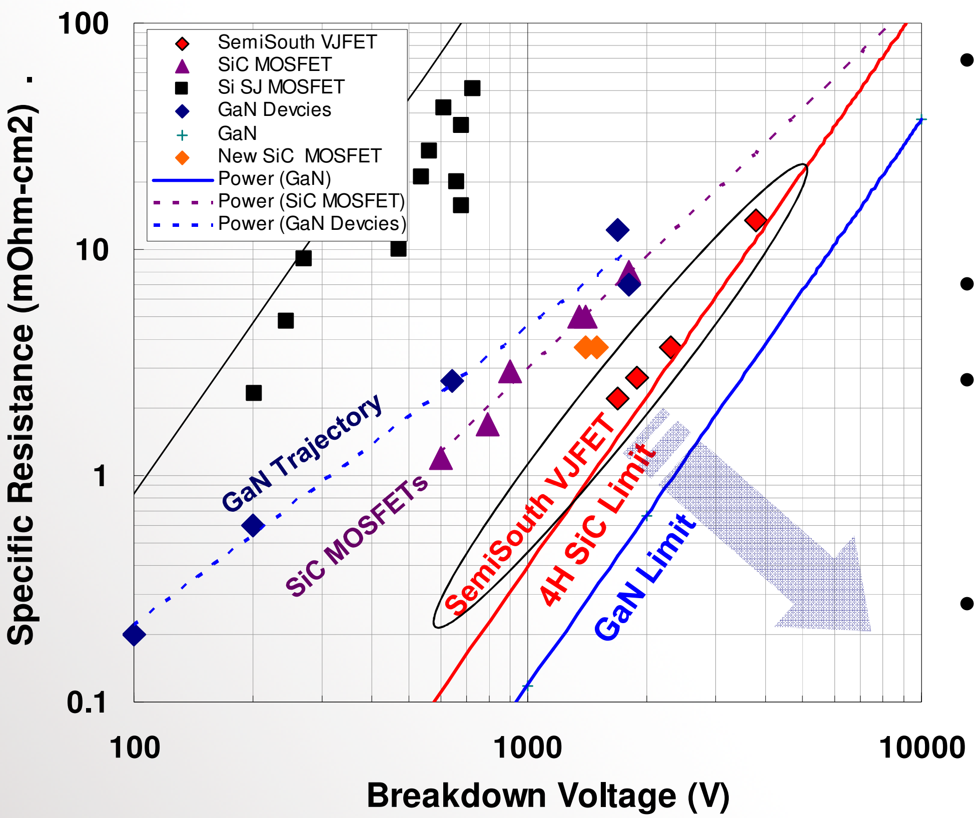
**SemiSouth Vertical-Channel JFET***




- (+) **Few mask layers**
- (+) **Low RPT**
- (+) **$R_{(on)sp} \approx$ 2-3 mΩ*cm²**

# SemiSouth Industry Leading Performance

***Proprietary Compact design leads to ultra-low specific on-resistance in power JFET (normally-on or normally-off versions available)***

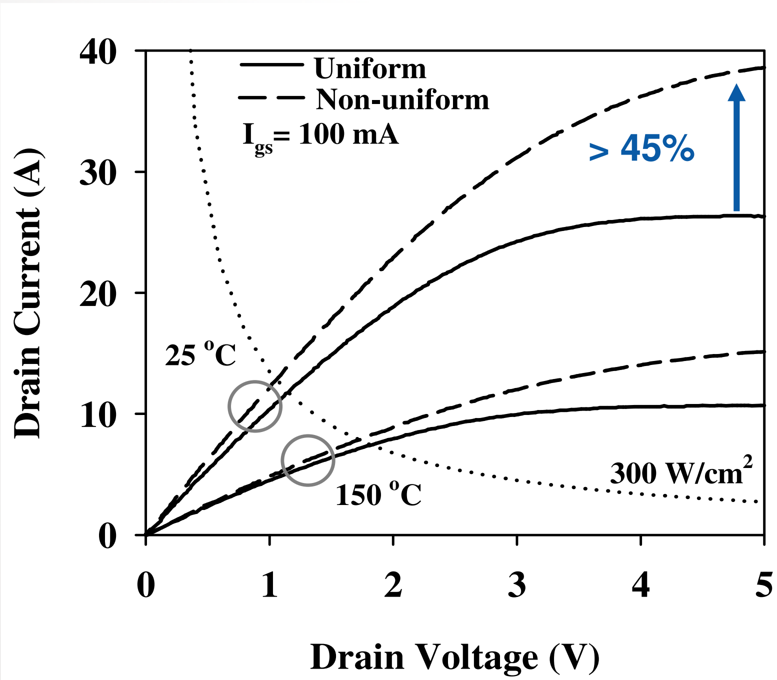



- SemiSouth first and only to offer TRENCH SiC JFET beginning in 2008
- Near theoretical specific $R_{DSON}$
- Normally-OFF OR Normally-ON use same device structure & manufacturing steps
- High reliability

# Advanced JFET Concepts

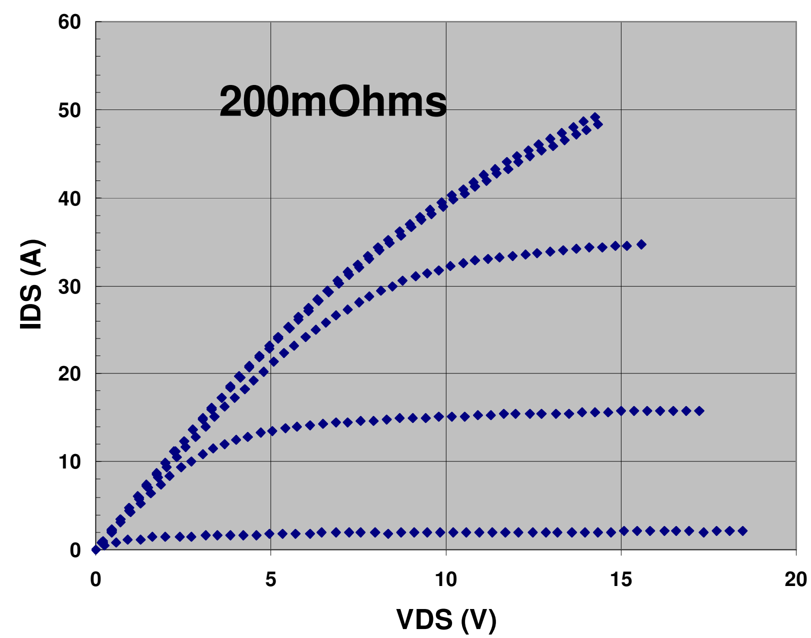
## High Current Normally-Off

- Demonstrated novel channel design for improved saturation current
- Significant increase in current and increased threshold range




## 3.3kV Design Normally-Off

- Normally-off SiC JFET – 3.8kV Design (edge termination limited)
- Exceptionally low Rds(on) = 200mOhms - > 50A saturation current



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# Comparison IGBT vs SiC

- Comparison of Vincotech Module
  With IGBT vs SIC JFET

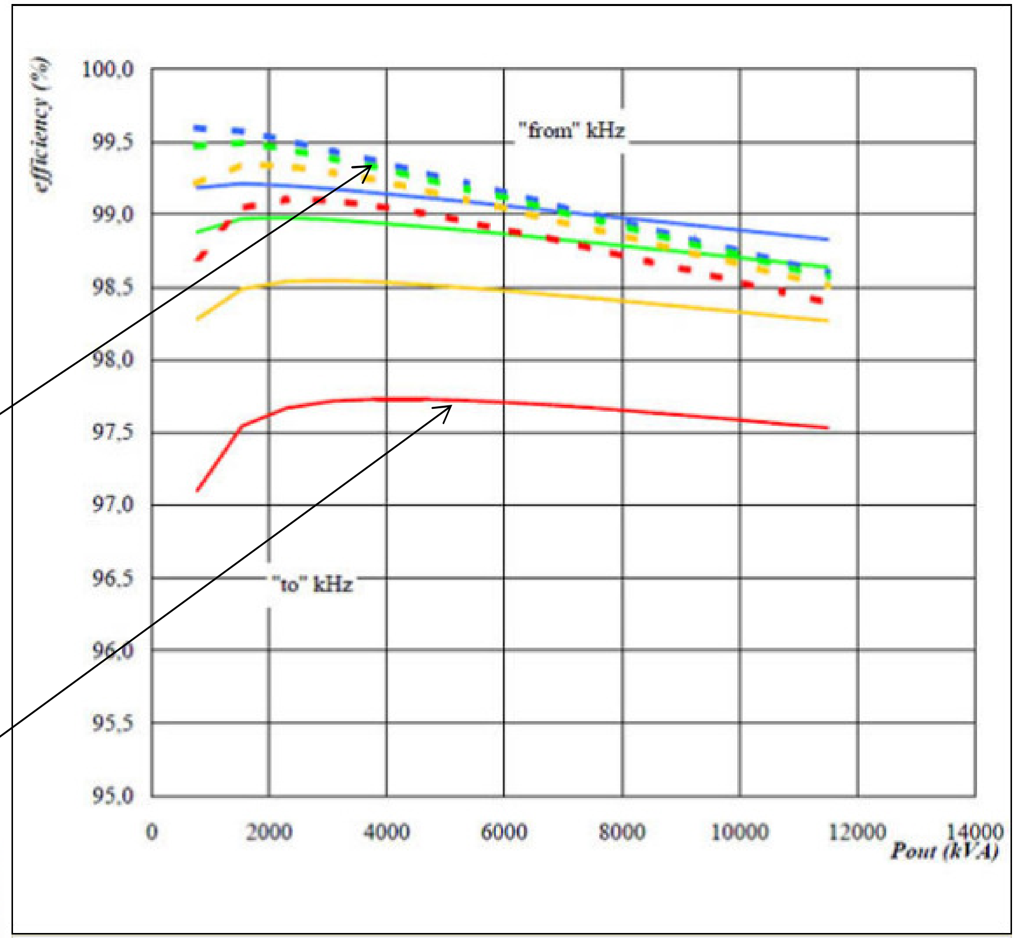
- Dotted Line SiC
  - Blue 8kHz -> Red 64kHz

**You can switch high Frequency**

- Non dotted Line: IGBT
  - Blue 8kHz -> Red 64kHz

**You can not switch high Frequency**

**JFETs gegen IGBTs**




© Vincotech

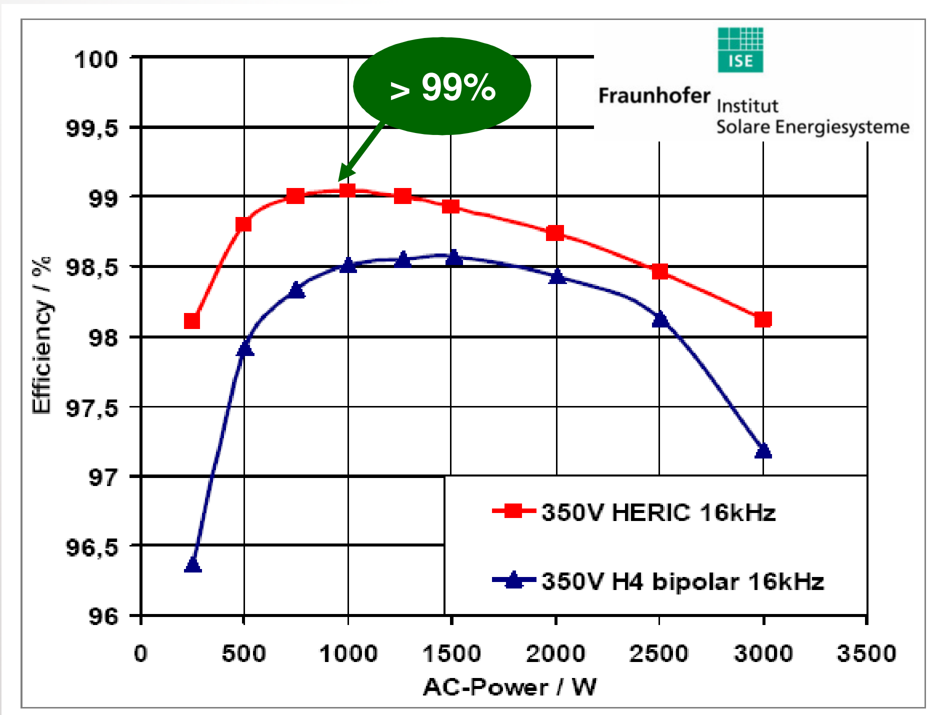
Bild 4: Effizienzvergleich von MNPC-Modulen mit Silizium-IGBTs (durchgezogene Linien) und SiC-JFETs (gestrichelte Linien) bei Schaltfrequenzen von 8 kHz (blau) bis 64 kHz (rot)

# Performance Validation

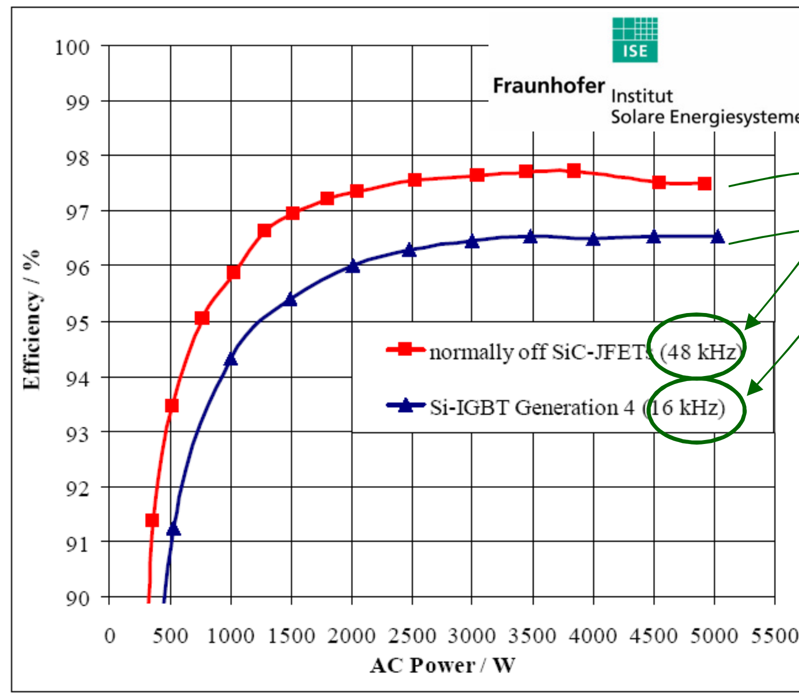
**WORLD RECORD Power Conversion Efficiency***

*"We now use junction field-effect transistors (JFETs) made of silicon carbide (SiC) manufactured by SemiSouth Laboratories Inc.. This is the main reason for the improvement", - Prof. Bruno Burger, leader of the Power Electronics Group at Fraunhofer ISE, July 2009 press release.*

- Single phase Heric®
- Commercial inverters @ 98%
- SemiSouth's JFET lowers losses ~ 50%



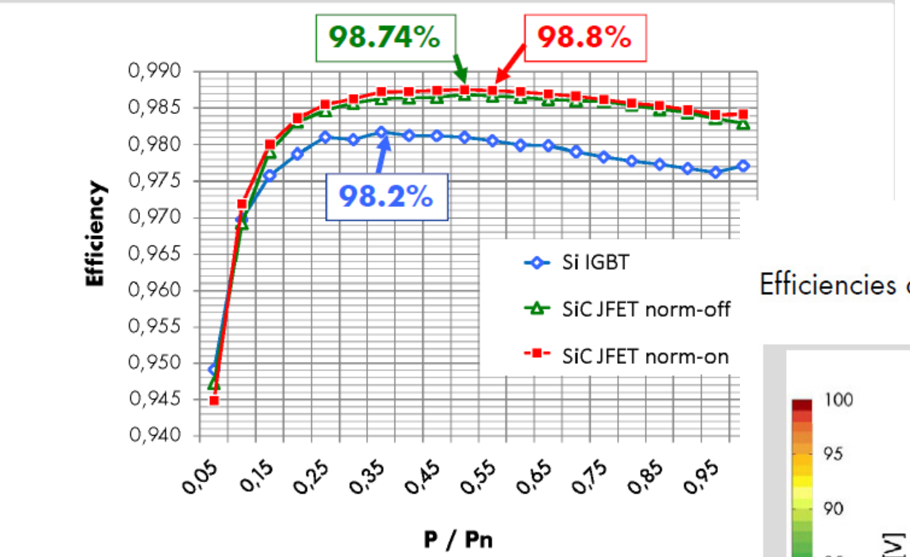

- Three phase full bridge inverter
- SemiSouth JFET ***boosts efficiency*** 1.2%
- SemiSouth JFET operates ***3X higher freq.***



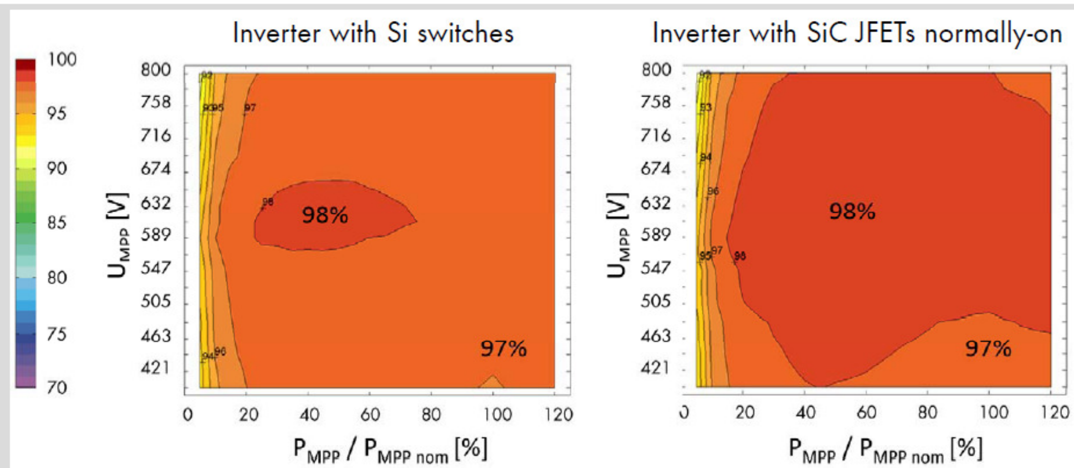

* Bruno Burger, Dirk Kranzer, "Extreme High Efficiency PV-Power Converters," EPE, Barcelona, Spain, 8-10 September 2009

# SMA SiC JFET Inverter

SemiSouth




Efficiencies at several DC link voltages (400V up to 800V) - „Photon test“




| Inverter \ Efficieny | $\eta_{max}$ | $\eta_{Euro}$ * |
|---|---|---|
| with Si semiconductor switches | 98,2 % | 97,3 % |
| with SiC semiconductor switches | 98,8 % | 97,9 % |

* European Efficiency – specific weighted average value

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- **Dr. Regine Mallwitz, SMA: SiC & GaN User Forum, Birmingham 2011**

SemiSouth

# SMA Quote about SiC

**1. Technical benefit** of SiC semiconductors

SMA

SiC devices promise

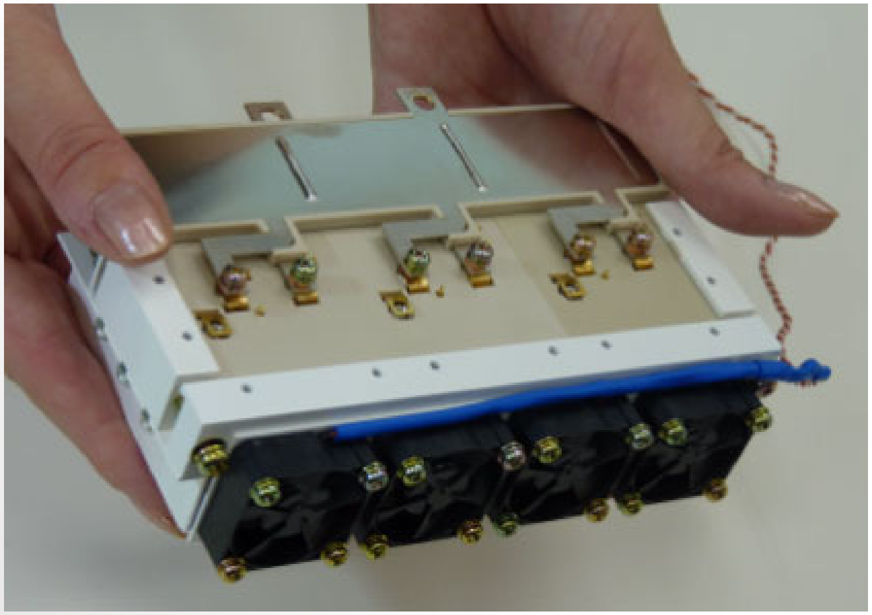
- low switching losses
- high rated voltages
- high operating temperature
- high radiation hardness

For PV inverters this properties offer possibilities toward

- **improved effiency** above 99% (at same switching frequency like today) → reduction of cooling effort → system size
- **higher switching frequencies** (at same level of losses like today) → reduction of system size → system costs
- **higher level of output power** (at same switching frequency and losses) → reduction of specific cost (per W)
- **higher DC input voltages**

- **Dr. Regine Mallwitz, SMA: SiC & GaN User Forum, Birmingham 2011**

# Automotive prototype inverter



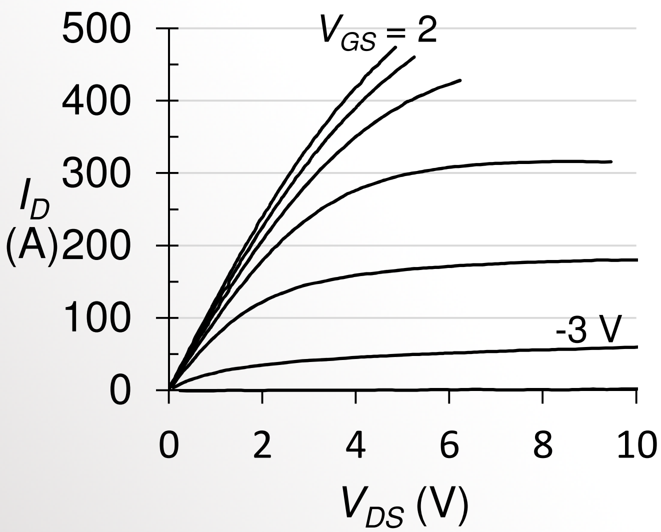
Sato, *et al*, International Conf. on SiC and Related Materials, Sept 2011

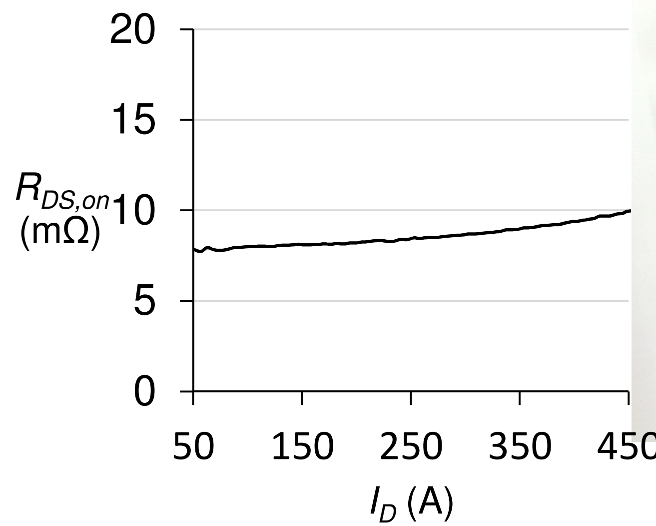
- Future Power Electronics Technology (FUPET) has developed an all-SiC-device-based three-phase inverter with a 0.5-liter volume, verified to achieve an output power density of ***30kWh/l***. "We believe this is the world's highest output power density for a small-volume inverter," commented FUPET officials.
- Using SiC junction field-effect transistor (JFET) devices procured from SemiSouth Laboratories, the power modules operate up to 200 ℃.
- 500cc inverter connected to a three-phase motor achieved ***15kW output***, which is 30kW/l or 30W/cc. At 15kW output, conversion efficiency was ***99%***.

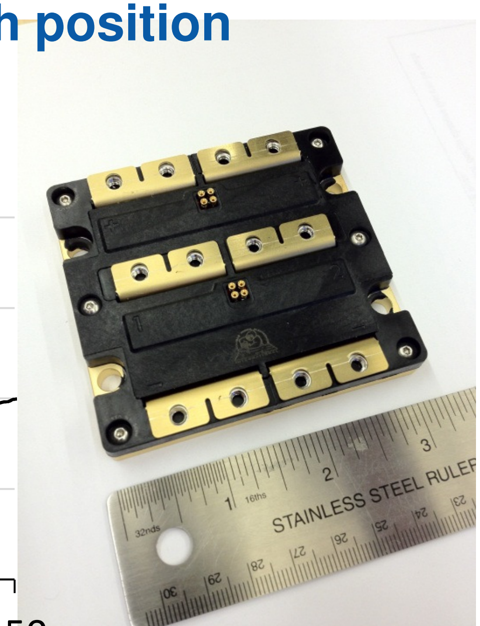
SemiSouth

# SiC JFET power module

## Only 36 mm$^2$ of JFET die area per switch position (4 x SJDC120R045)




| Switching energies at 25 ℃ of SiC VJFET modules ($I_D$ = 100 A) and a Si IGBT module ($I_C$ = 150 A) | | | |
|---|---|---|---|
| | Turn-on energy | Turn-off energy | ***Total switching losses*** |
| **Enhancement-mode SiC VJFET** | 0.72 mJ | 0.46 mJ | **1.18 mJ** |
| **Depletion-mode SiC VJFET** | 0.33 mJ | 0.90 mJ | **1.23 mJ** |
| **Si IGBT (Infineon)** | 8.5 mJ | 8.5 mJ | **17.0 mJ** |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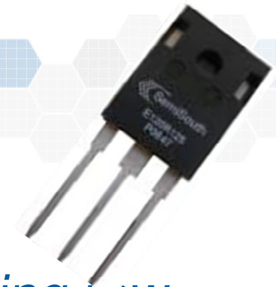
# Summary



- ❑ SiC trench JFET production since 2008
- ❑ *Size and weight reduction are key elements to fight increasing raw material cost*
- ❑ *High frequency (power density) with improved efficiency is key to reducing weight and cost*

***→ HV SiC devices are possible, and scaling to higher currents***

- ❑ *What devices are needed for MV – HV applications?*
- ❑ *Initial insertion applications?*
- ❑ *Device requirements?*
- ❑ *Cost targets?*

Skip

Scozzie

# Status of SiC Power Devices for Compact High-Efficiency High-Temperature Power Circuits

*Presented to NIST's High Megawatt PCS Workshop*
*May 24, 2012*


C. J. (Skip) Scozzie
Energy and Power Division
U.S. Army Research Laboratory
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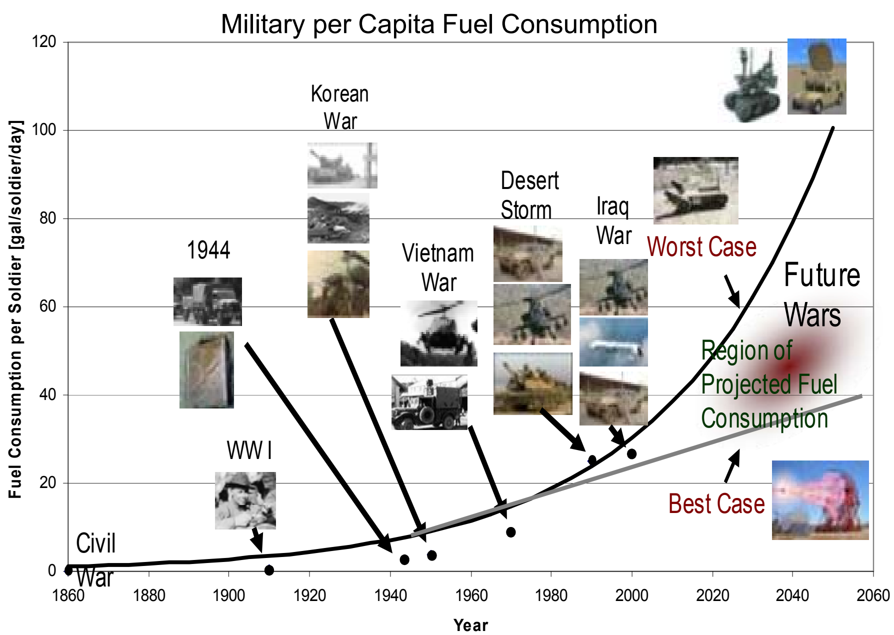
TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

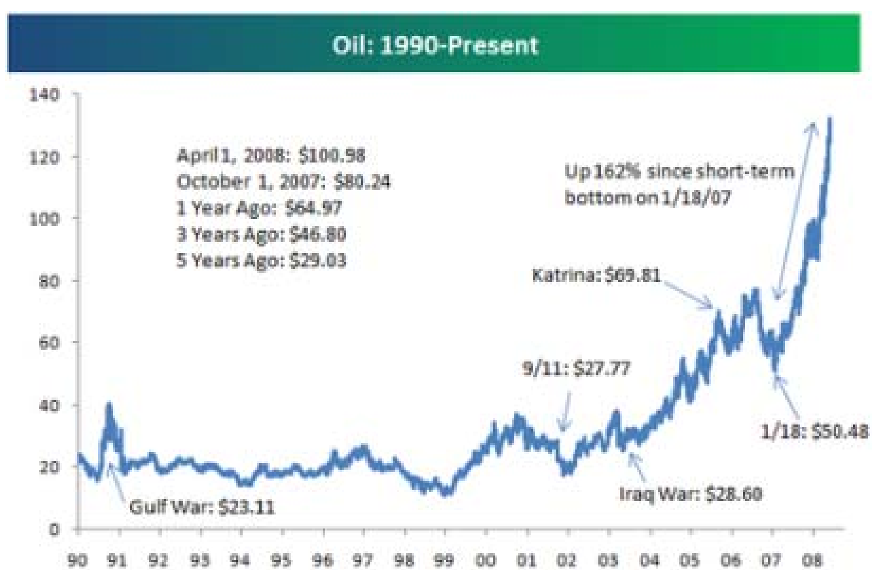
# Outline

- Army Platform Power Requirements and Motivation for SiC Power Device Research
- Status of Continuous SiC Power Devices
  - ✓ Technology Background
  - ✓ Results of 1,000 hr Power Module Evaluation
  - ✓ Future Plans
- Status of Pulse SiC Power Devices
  - ✓ Technology Background
  - ✓ Pulse Power - Results of 1,000 shot Evaluations
  - ✓ Future Plans
- Summary

# Army Power Problem

- ***Power loads continue to rise on all military platforms. Mission Capability on current and future platforms is driven by effective use of electric power.***
    - ***Deficiency - Limited Space/Payload available to provide power without compromising mission load payload allocation***
    - ***SiC-based converters provide greater power density and finer control than Si-based converters – however maturity /reliability and cost is still a risk factor to PMs.***
    - ***Focus on increased efficiency and temperature for size reduction and fuel economy***



RDECOM

# Power & Energy Application Regimes


| DOMAINS: | Soldier, C4ISR | C4ISR, Air, Ground | Ground, Effects |
|---|---|---|---|
| | MicroWatts to 10s of Watts | 100s of Watts to 100s of kW | Up to 1000s of MW |

# SiC Power Electronics Army Benefits

**Reduced SWAP, reduced cooling requirements, increased efficiency at high voltage and higher operating temperatures. Overall, easier to integrate onto military ground vehicles than silicon based systems and provide significant deltas in fuel economy and mobility performance.**

| Category | Army Fuel Consumption (M gal / yr) | |
|---|---|---|
| | Peacetime OPTEMPO | Wartime OPTEMPO |
| **Combat Vehicle** | **30** | **162** |
| Combat Aircraft | 140 | 307 |
| **Tactical Vehicle** | **44** | **173** |
| **Generators** | **26** | **357** |
| Non-Tactical | 51 | 51 |
| **Total** | 291 | 1040 |

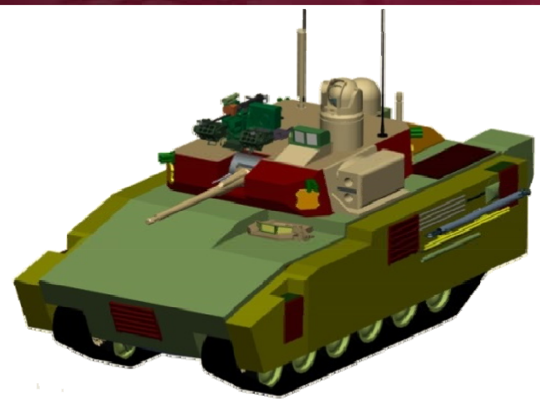
**Def. Sci. Board Task Force on DoD Energy Strategy Report (2008, pg. 41)**

- **Size / Weight:** Up to 2X smaller and lighter compared to Si circuits.
- **Power:** 70 % more efficient than Si Circuits and, hence, 1- 3 % fuel savings for mechanical-drive platforms and even greater for HEVs (operated at ≤ 3 MPH).
  - **For 2% efficiency increase in combat vehicles alone, savings could be $648 M/yr during wartime OPTEMPO; additional 3X in savings could be realized when you include Tactical Vehicles and Generators.**
- **Cooling:** greater operating temperature (>100°C coolant) and high efficiency, cooling system SWAP is significantly reduced.
- **Reliability:** Si power electronics (80°C coolant) have no thermal margin. SiC power electronics (100°C coolant) have >60°C margin and can provide **'Limp Home' functionality**.
- **Endurance:** ability to sustain operations for an extended time without support or replenishment.

# Power Electronics
# High Temperature Requirements

- Current acquisition programs allow separate coolant loops for power electronics ranging from 30°- 70°C
- Next-Generation vehicles will reduce the number of vehicle cooling loops; power electronics would be cooled at same temperature as engine (up to 113°C for pressurized WEG systems)
- Resulting in junction temperatures up to 200°C
- Engine compartment temperatures up to 150° C upon start up
- Some conductively cooled applications that will operate in a 70°C ambient environment
- Air-cooled applications for battlefield power generation could required Junction temperatures > 200°C
- Requiring SiC high-frequency operation at high-temperature will push the limits of the devices as well as the packaging technology………not to mention the limits on passive components.
- Technology will need to be transition by FY17 to cut into Next-Gen vehicle designs

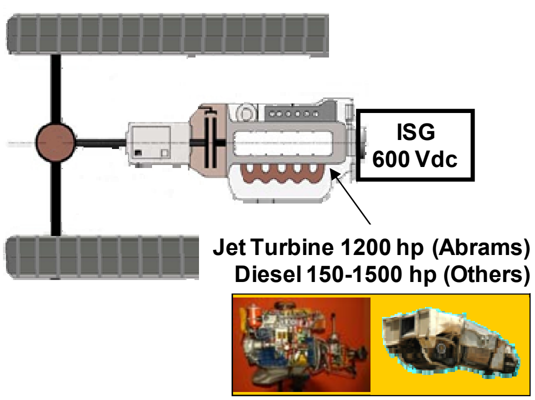
# Electrical Power Architecture for Mechanical Drive Platform

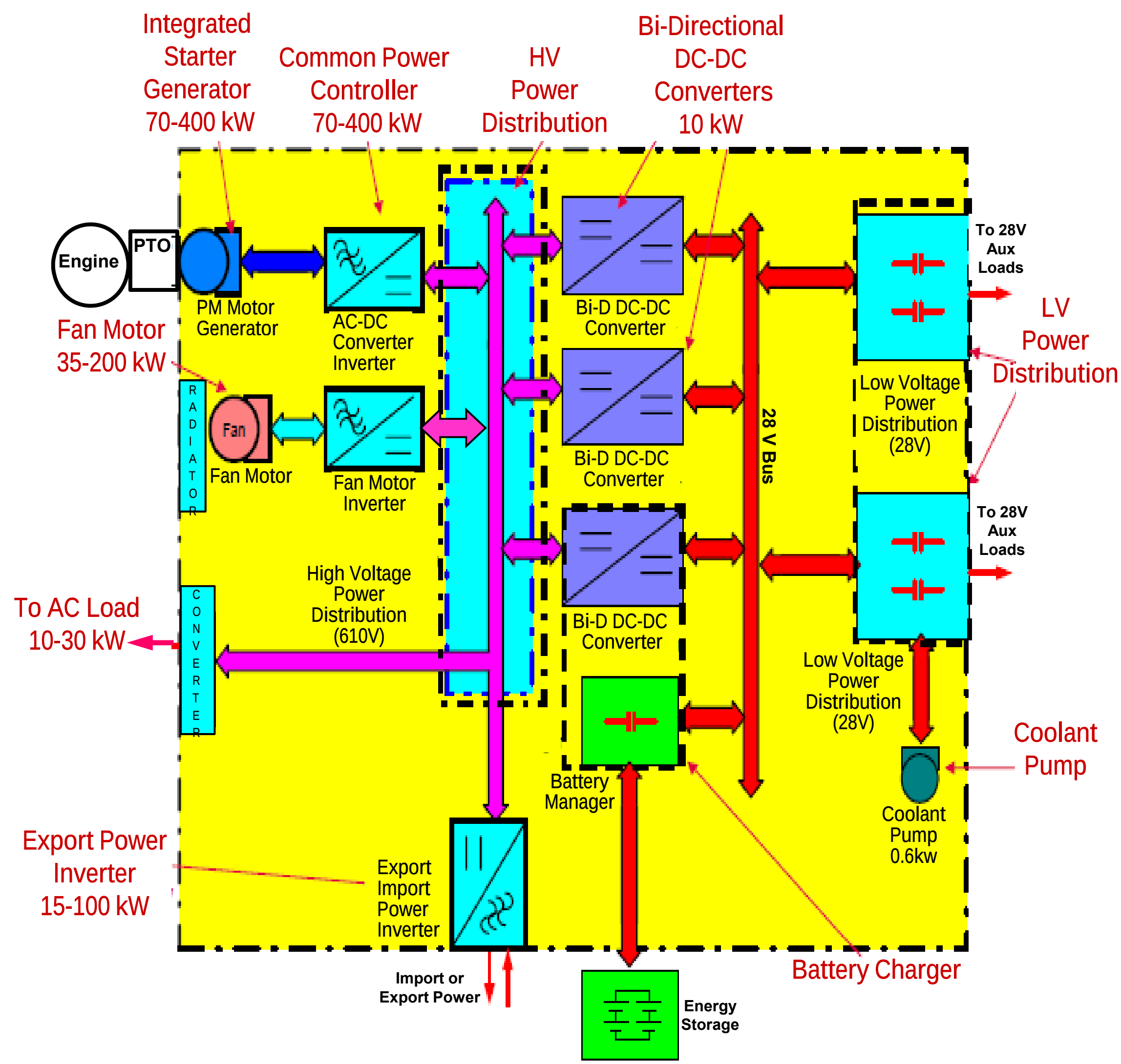


## Electrical Architecture Attributes:

- 600 V Power generation
- 28 V Battery
- 28 V and 600 V DC busses
- 28-600 V Bi-directional DC-DC conversion
- 240 V AC Export/Import Power capability

**Power:** 5 – 200 kW **Current:** 30 - 700 A
**Temp:** 80°-150°C

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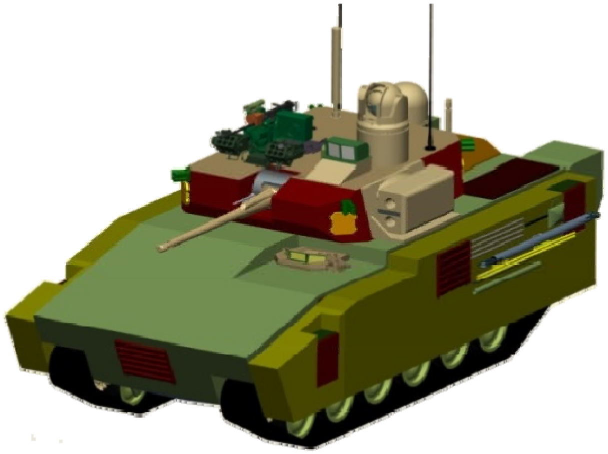
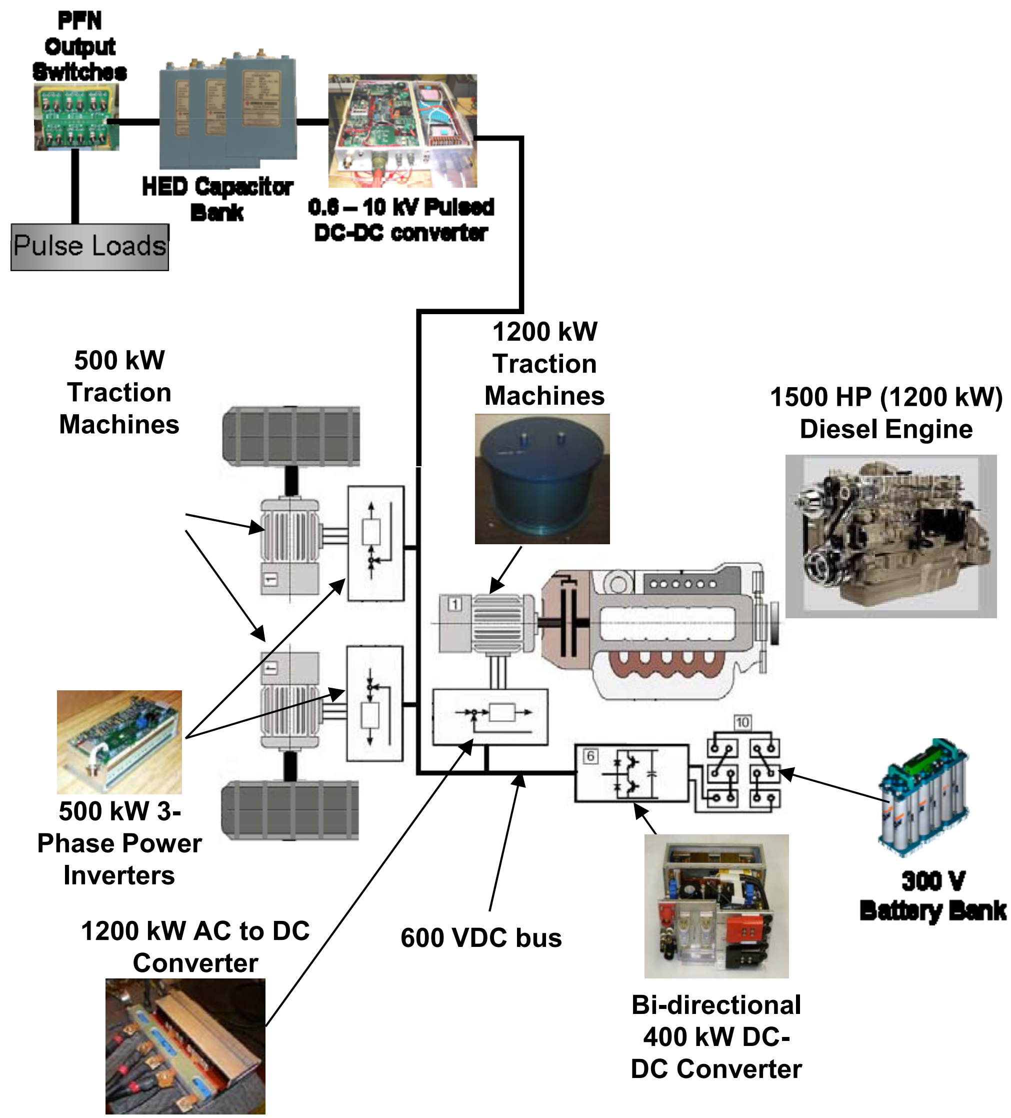
# Electrical Power Architecture for Hybrid-Electric Drive Platform



Electrical Architecture Attributes:

- 600 V Power generation
- Electric Drive ✓
- 300 V Battery ✓
- 300-600 V Bi-Directional (Batt.-Bus) Converter ✓
- 600 V and 28 V Busses
- 600-28 V DC-DC conversion
- 240 V AC Export/Import Power capability

**Power:** 5 – 1200 kW **Current:** 30 - 2400 A
**Temp:** 80°-150°C

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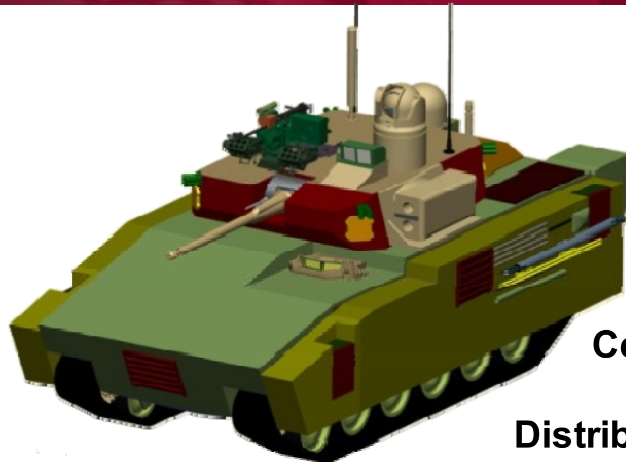
# Army Platform Modernization
# Pulse Power Electronic Survivability Architecture



**Centralized System under armor**
**or**
**Distributed Systems in multiple locations for energy distribution and redundancy**

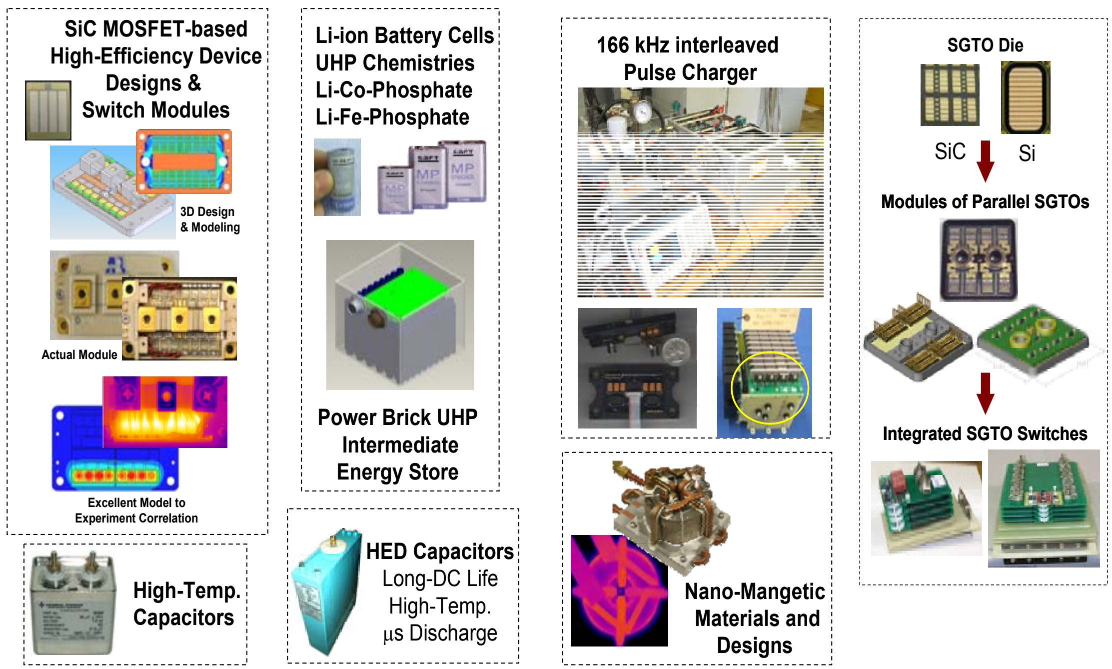
## Rationale:

- Support hybrid armor, emerging survivability/lethality
- External distribution (uncooled)
- Local high power energy store w/o engine operating

## Challenges

- High temp, high freq, high current, low loss switching
- High freq/ high Bsat/ high temp advanced magnetics
- High voltage "power brick" battery
- High temp/ density storage & conversion capacitors
- Ultra-Fast Hi-voltage GW switches
- Cooling through conduction only

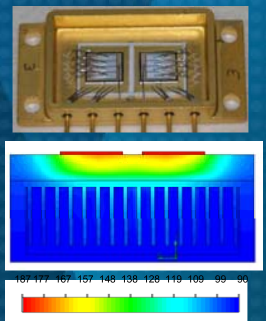
**Voltage:** 10-450 kV **Current:** 0.1-250 kA
**Power:** MW-GW **Temp:** 60-100°C



# High-Temperature High-Efficiency SiC MOSFET Power Modules

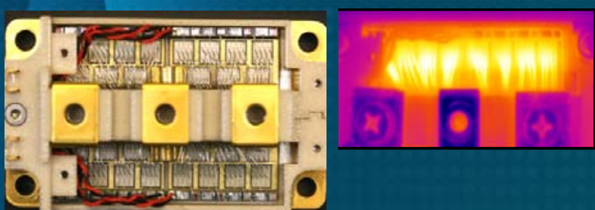
- **In 2007 Q1, PM FCS requested ongoing SiC ManTech program (FY04-09) to accelerate SiC power MOSFET & Diode development to replace Si power electronics**
  - ✓ Lack of desired top speed for MGV HE drive due to losses in Si power devices
  - ✓ Potential for single point failures of Si TDS power modules at high operating temp.
- **By end of ManTech program, SiC MOSFETs had been matured to 80 A (16X increase) and diodes matured to 100 A (10X increase)**
- **FCS TDS developmental power module populated with 900 A of SiC power devices**
  - ✓ Initial operation using both 80˚ and 100˚C coolant for 200 hours (FY10)
  - ✓ 70 % reduction in losses (at both coolant temp's) over Si TDS module at 80˚C
- **Subsequent TDS modules populated with 1,000 A of SiC power devices (FY11)**
  - ✓ 1000 hr (80°C coolant) evaluation completed maintaining same efficiency
  - ✓ 1000 hr (100°C coolant) evaluation is planned for this FY
- **Under additional funding (FY11 ARA) SiC MOSFET design matured to 100 A**
  - ✓ Subsequent power modules to be implemented and evaluated at 100˚C WEG this FY
- **PM GCV requests cont'd SiC investment to mature power devices for transition in FY17**
  - ✓ Mature high-reliability SiC ManTech processes required for 10,000-15,000 hr life time

# 1.2 kV Silicon Carbide Power Modules Progression from 90 to 1,000 A

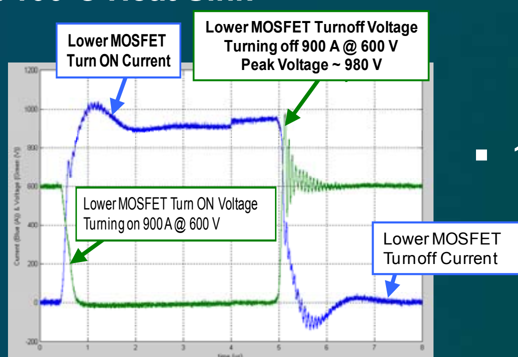


Boost converter test conditions:
- $I_{RMS}$ = 92-A
- $T_j \approx$ 186 °C
- 90 ˚C PGW coolant
- $F_{SW}$ = 10-kHz
- Duty = 69%
- $V_{IN}$ = 160-V
- $V_{OUT}$ = 491-V

**Paired Large-area (0.6cm²) SiC MOSFET Die Operating at $T_J$ = 186˚C in Boost Converter**



**Near-perfect SiC MOSFET Current Sharing In 1200 V / 400 A Module Operating at 100˚C Heat Sink**



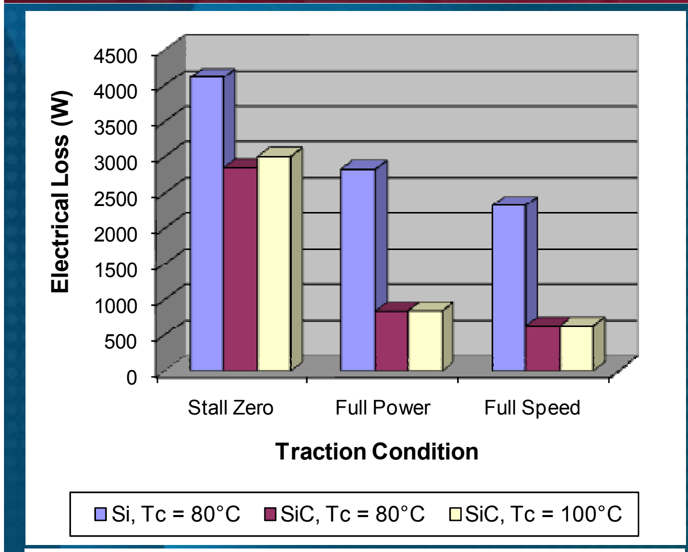

**1200 V / 900 A Module Operating at 80˚C Heat Sink Under Stall-Zero Condition for 200 hours**

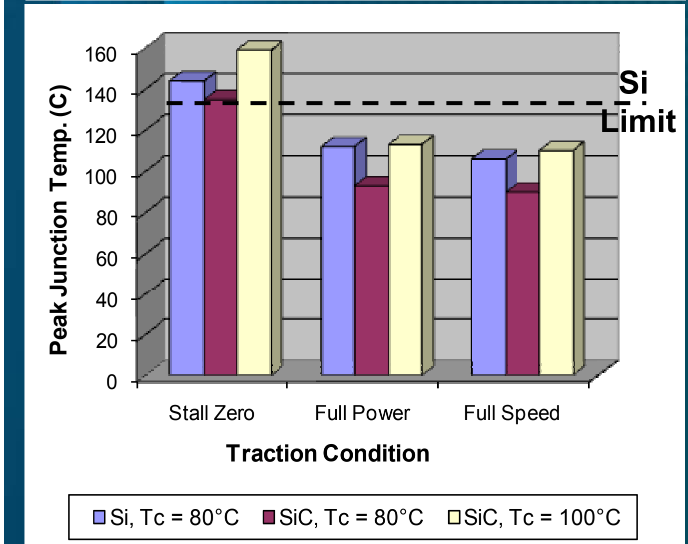
## ❑ Demonstration of SiC MOSFETs and Diodes in High-Temperature Power Modules from FY 2008 to present

- 1200 V / 90 A power module demonstration
  - o Operated using 90°C coolant
  - o Paired 50 A Power Die operated up to 186˚C junction temperature in boost converter
- 1200 V / 400 A power module demonstration
  - o Operated using 80˚ & 100˚C coolant
  - o 50 A die show near-perfect current sharing
- 1200 V / 900 A power module demonstration
  - o Operated using 80˚C coolant for over 200 hours
  - o Under Stall-Zero condition
  - o 80 A die show near-perfect current sharing
- 1200 V / 1000 A power module currently under test
  - o 1000 hr evaluation planned for initial reliability
  - o Operating using 80˚C coolant
  - o Drive profile continuously cycled
  - o Currently at > 900 hrs of operation with no significant changes in device characteristics

Cree Devices

# High-Temperature High-Efficiency SiC MOSFET Power Modules




**Results from 200-hr Evaluation for 250 kW Traction Drive Application**

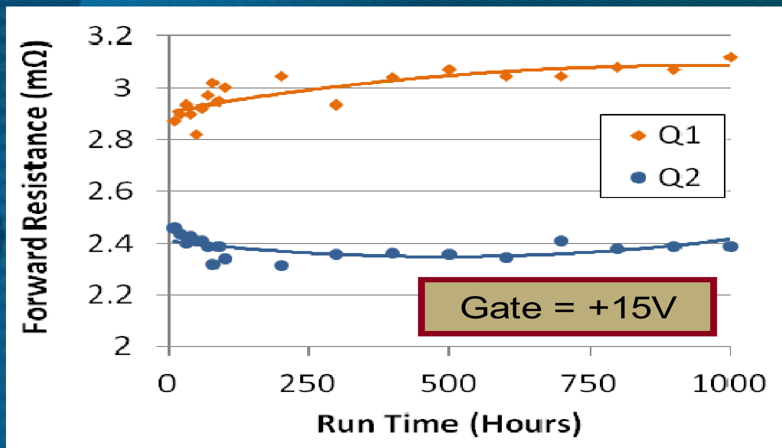
## Demonstration of SiC MOSFET TDS Power Modules

- 1200 V / 900 A developmental power module demonstration
  - o Operated using 80˚C & 100°C coolant for > 200 hours
  - o Under Stall-Zero condition
  - o 25 – 40 % reduction in losses over Si for fault condition
  - o 70% reduction in losses for normal use condition over Si (estimated based on exp. Data)
- 1200 V / 1000 A fully-functional power module
  - o 1000 hr evaluation for initial reliability completed
  - o Operating using 80˚C coolant
  - o Drive profile continuously cycled (Churchville B course)
  - o No significant changes in module characteristics
  - o 70% reduction in losses for normal-use condition over Si (experimentally confirmed)
  - o 1000 hr evaluation planned at 100°C heat sink

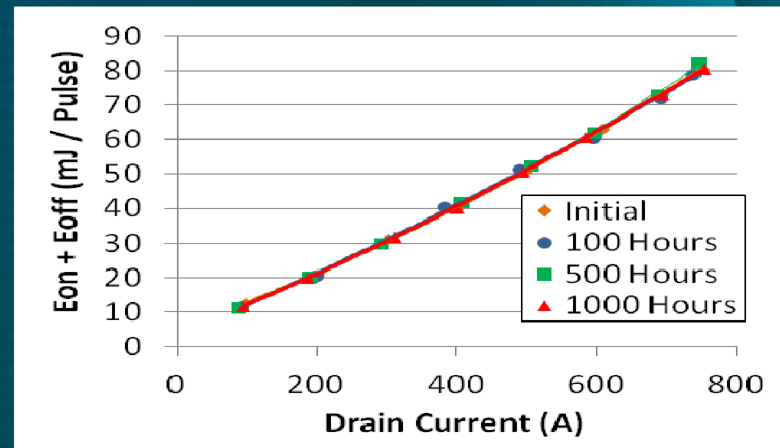
- **Si Modules with 13.9 $cm^2$ IGBTs and 8.4 $cm^2$ diodes**
- **SiC Modules with 5.6 $cm^2$ MOSFETs and 3.1 $cm^2$ diodes**

**Cree Devices**

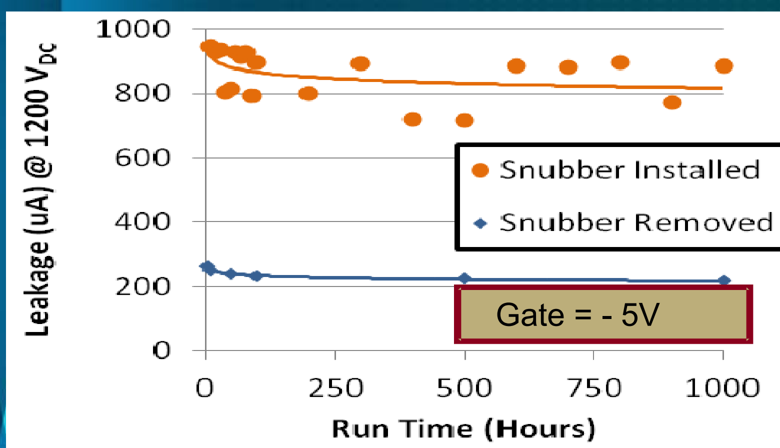
# Results from1000 hr Evaluation of Fully-Functional SiC Power Module at 80°C Heat Sink



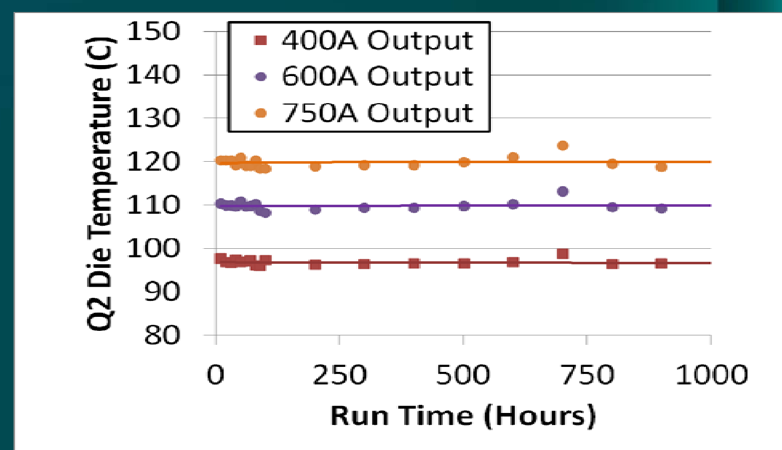

Stable Low $V_f$ when on




No change in Total Switching Energy




Stable Low leakage when off




No change in Die Temperature

**Cree Devices**

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

# Status & Future Plans
# SiC Continuous Power Devices

## ❑ GEN-1 (ManTech) 1.2 kV / 80 A SiC MOSFETs and Schottky Diodes

- ✓ Capability of SiC Power Modules to operate at high temperature (80°-100°C WEG) and provide 70 % increase in efficiency over Si-based modules (200 hr evaluation)
- ✓ Initial reliability of SiC Power Module established at 80°C WEG for 1,000 hr under 'Churchville B' course conditions with no degradation in efficiency
- ✓ Same Power Module to be put under another 1000 hr test at 100°C WEG this FY

## ❑ GEN-1 (ARA) : 1.2 kV / > 100 A SiC MOSFETs

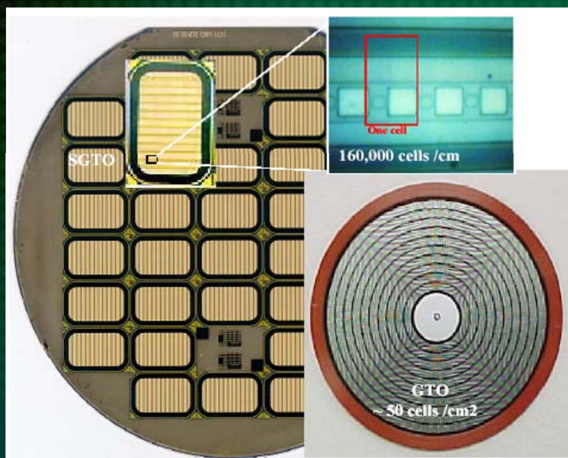
- ✓ Next GEN devices with same die size as GEN 1 but with increased efficiency
- ✓ Power module to be implemented and 1000 hour evaluation at 100°C WEG under 'Churchville B' course conditions

## ❑ GEN-2: 1.2 kV / >200 A SiC MOSFETs (WEG >100°C)

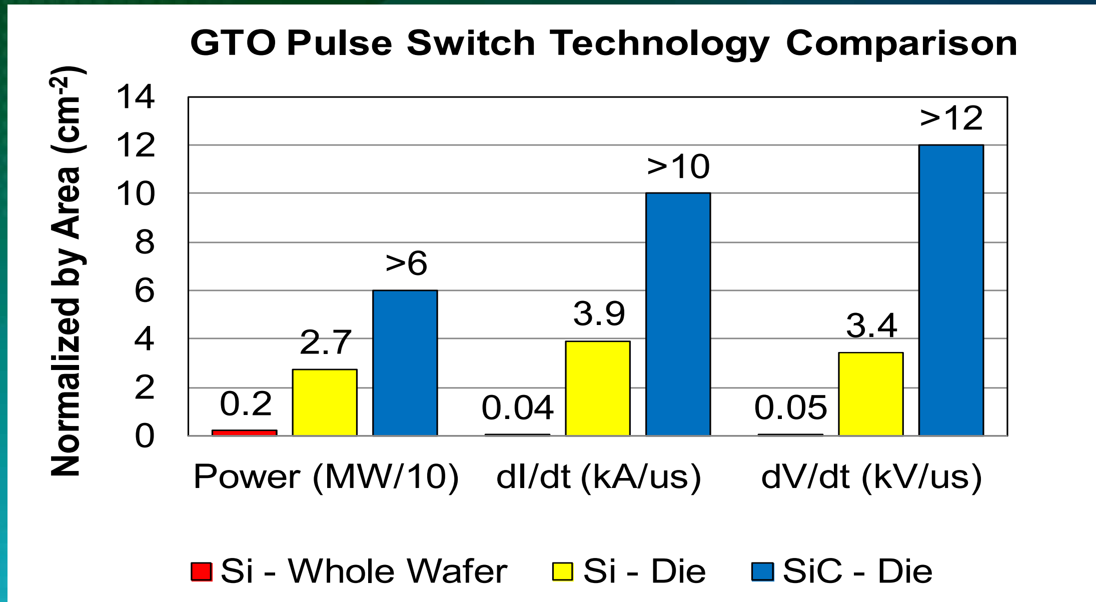
- ✓ Proposed and current programs to increase power rating and mature technology to MRL8,TRL7 (at enhanced reliability and reduced cost) by FY16
- ✓ Current programs will mature to only MRL6/7, TRL6; and at increased cost
- ✓ Proposed programs need to be fully funded to insure transition in FY16/17

# Pulse Switch Technology Comparison

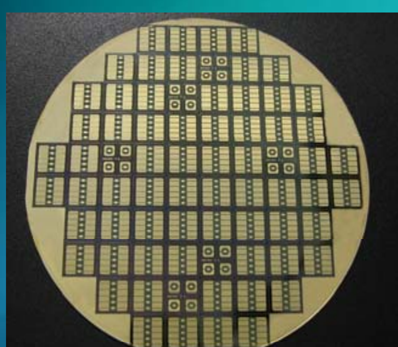
## Si Whole Wafer GTO vs. Si SGTO Die




**Basic Die (3.5 cm²) 20 kA, 6 kV**
**14 kA/µs, Turn-on Gain = $10^6$**

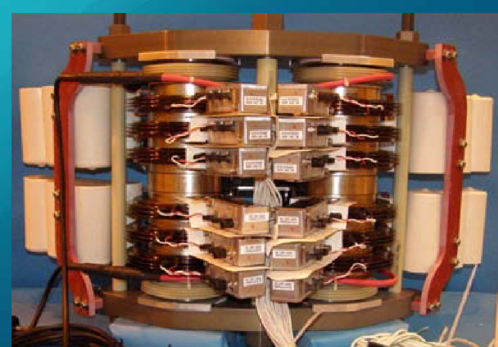



## SiC SGTO Die on 4" Diam. Wafer



**Basic Die (1.0 cm²) 5 kA, 12 kV**
**10 kA/µs, Turn-on Gain = $10^6$**

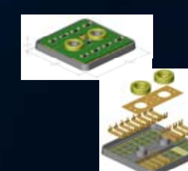
## Packaged Pulse Power Switch Assembly (400 kA)



**Si 8 kV Clamped Whole Wafer**
**With Snubber Caps**

**Si 16 kV Die-Based**
**No clamps, No Snubbbers**

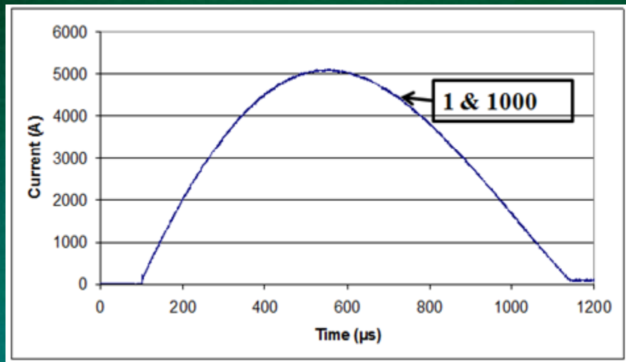
**Building Block Module**



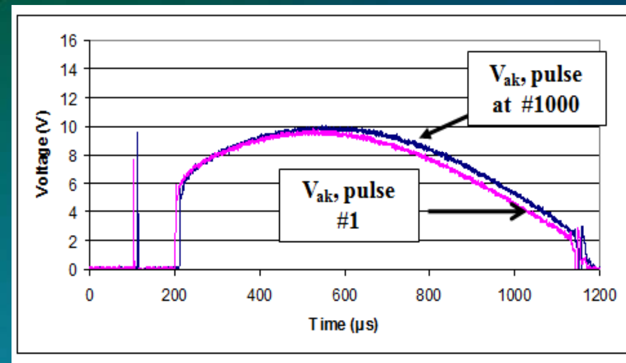
**8-Die Module**
**for Si or SiC**

# Results of Small-Scale Module (2.4 cm2 die area)
## 1000-Pulse tests at Wide and Narrow Pulse Width

### Wide-Pulse Performance

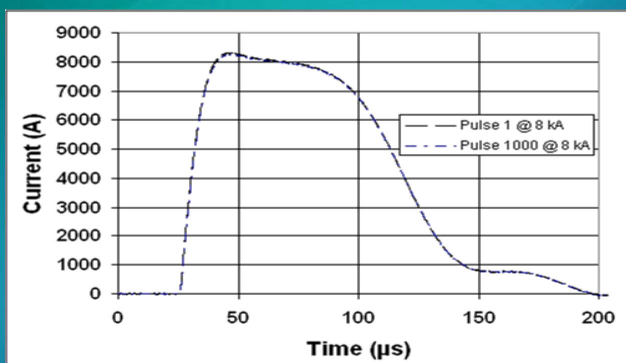



SiC SGTO module peak current.
Overlay of pulse 1 and 1000.

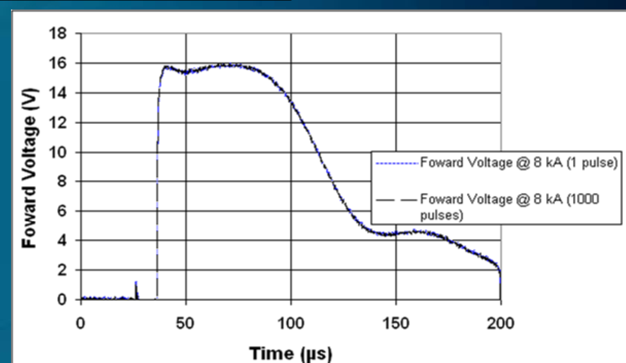



SiC SGTO module forward voltage drop.
Overlay of pulse 1 and 1000.

### Narrow-Pulse Performance



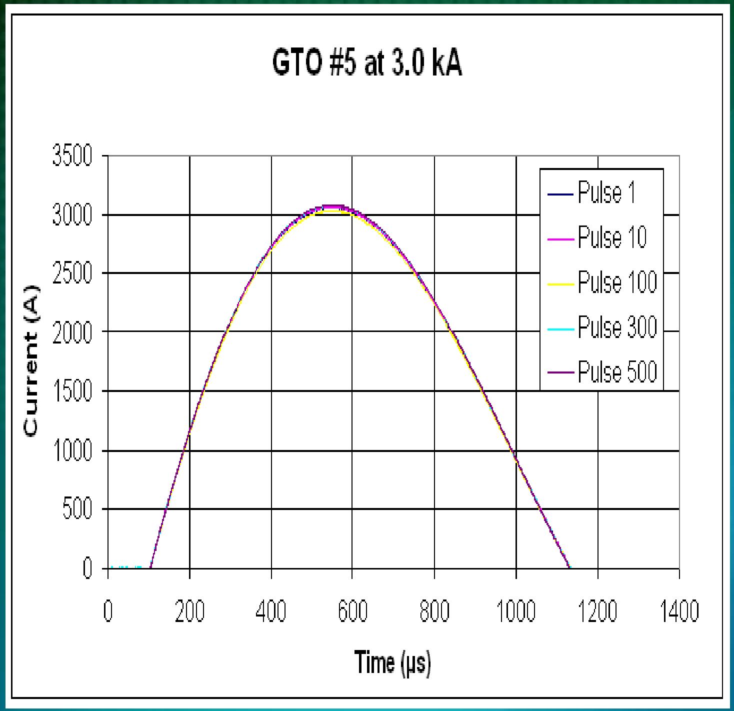

SiC SGTO module peak current .
Overlay of pulse 1 and 1000.

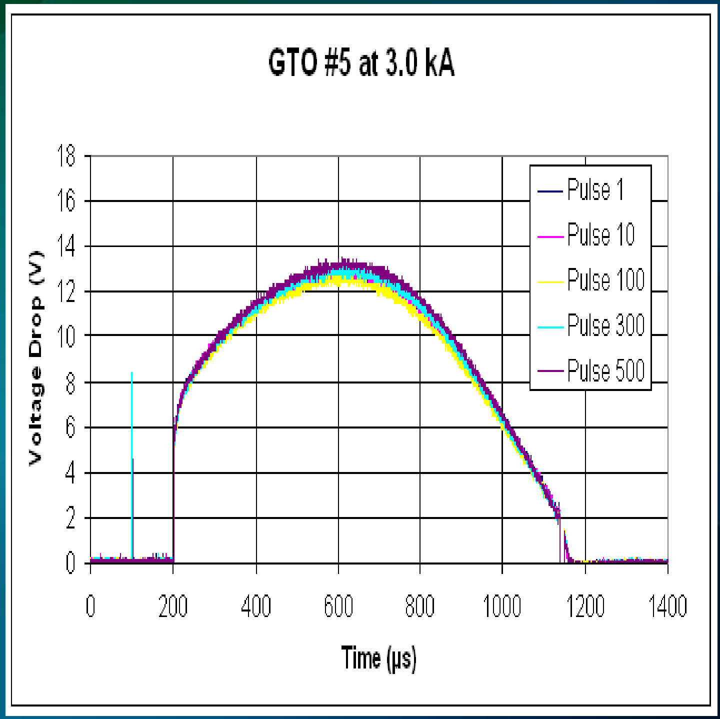



SiC SGTO module forward voltage drop
Overlay of pulse 1 and 1000.

**Cree Devices**

# Initial Results for Wide Pulse Evaluation 1 cm2 SiC GTOs

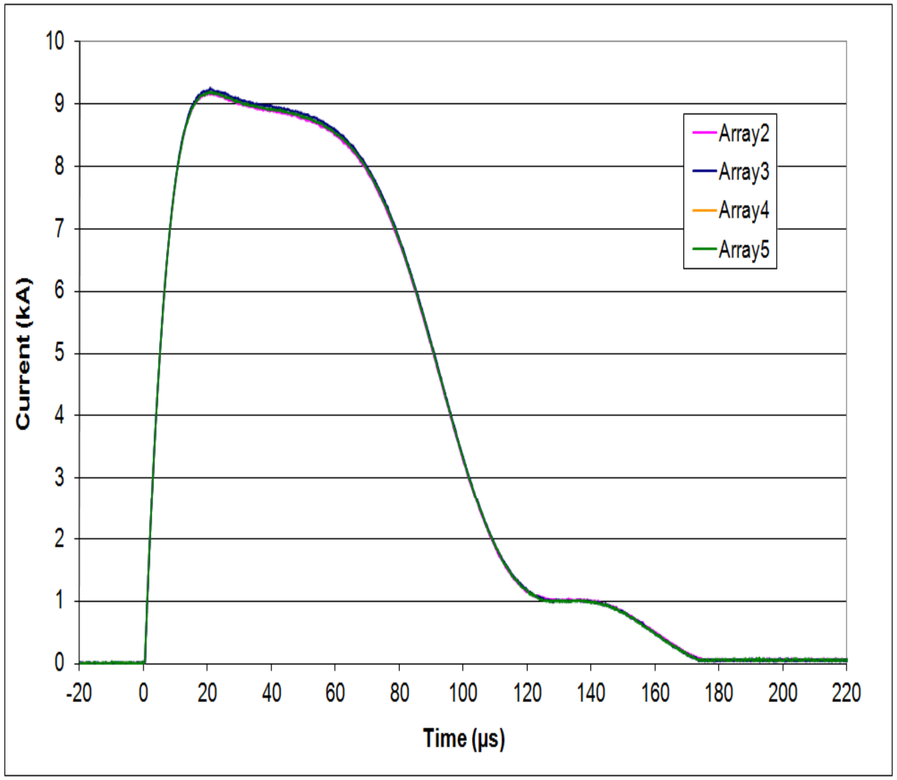


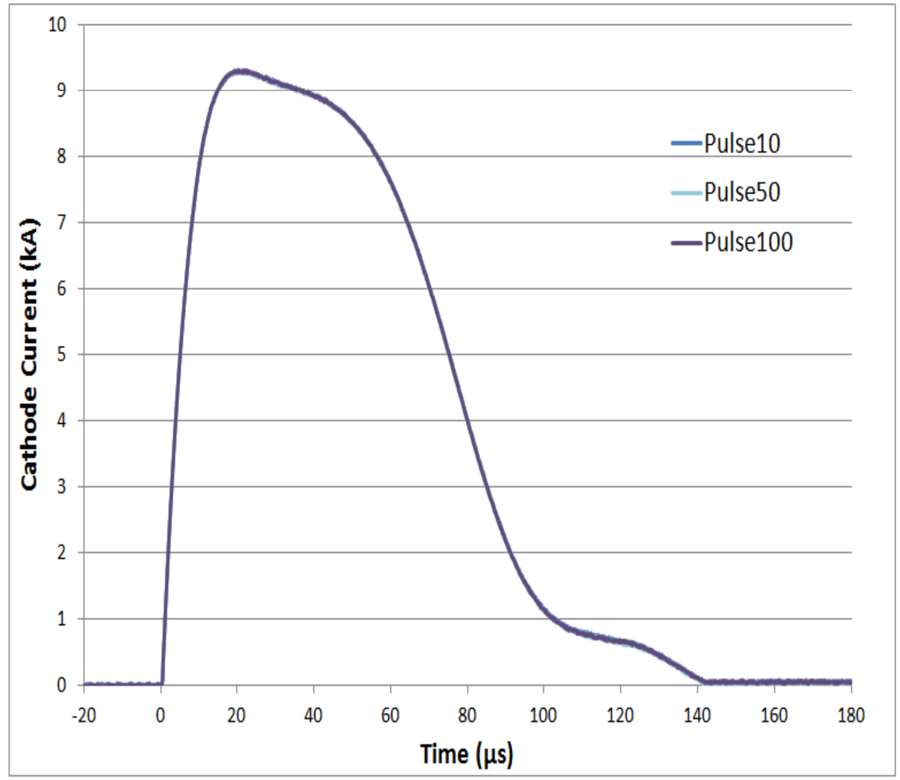




- ✓ **50 % Increase in Current Density over previous Gen Switch (0.6 $cm^2$ )**
- ✓ **Data has been taken (but not available) to show 1 cm2 die provides 5 kA at narrow pulse width application**

**Cree Devices**

# Initial Results for Narrow Pulse Evaluation SiC SGTO 1 x 2 Arrays (1cm² die)




Four SGTO arrays (2 $cm^2$ die area)
each switched at 9 kA

Array #3 (2 $cm^2$ die area)
Initially switched at 9 kA for 100 pulses

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

# Status and Future Plans for Si and SiC Pulse Switches

- **Si SGTO Since 2004:**
  - ✓ Baseline Die size (3.5 $cm^2$) has remained the same
  - ✓ Increased Peak current (from 10 to 16 kA) and Blocking Voltage (from 4 to 6.5 kV)
  - ✓ Developed 'Stitch' Die at increased die size (2 X) and Current (2.5 X)
- **Si SGTO Future Work as Near-term solution**
  - ✓ Optimize packaging to handle increased current and voltage for baseline die
  - ✓ Continue with Stitch Die to optimize current density and voltage (6.5 kV)
  - ✓ Optimize standard module package for 'Stitch' device's increase current density

- **SiC SGTO Since 2004:**
  - ✓ Increased Die size (from 0.16 to 1 cm2)
  - ✓ Increased Peak current (from 0.8 to 5 kA) and Blocking Voltage (from 2 to 12 kV)
- **SiC SGTO Future Work as Mid- to Far-term solution**
  - ✓ Increase die size up to 2 $cm^2$
  - ✓ Increase peak current to 15 kA and Blocking Voltage to 15-20 kV
  - ✓ Optimize Si standard module package for SiC increased current and voltage

- **Current program will mature to only MRL6, TRL6 and at increased cost**
- **Proposed programs need to be fully funded to insure transition in FY16/17**

# SiC Power Switch Summary

- **Continuous Power Applications**
  - ✓ SiC TDS module operating at 80° and 100°C WEG with 70% greater efficiency than Si TDS module; and at 40% replacement.
  - ✓ Proposed and current programs to mature MOSFET to 300 A @ > 100°C WEG

- **Pulse Power Applications**
  - ✓ Si SGTO die pulse switch operating at 10X power density of Si whole-wafer switch
  - ✓ SiC SGTO die operating at 2 X greater power density than Si SGTO die
  - ✓ Proposed and current programs to mature SiC switch power density by another 2-3X at increased efficiency.

- **Above component work can reduce power system size by up to 2X for continuous and 4X for pulse power applications with efficiencies at >2X vs. Si-based systems**

- **Proposed programs need to be fully funded to insure transition in FY16/17**
  - ✓ Current programs will mature to only MRL6, TRL6 and at increased cost

Sharon

Beermann-Curtin

# High Voltage Silicon Carbide NIST Workshop May 2012

Next Generation Technologies for Today's Warfighter

Sharon Beermann-Curtin –Ofice of Naval Research

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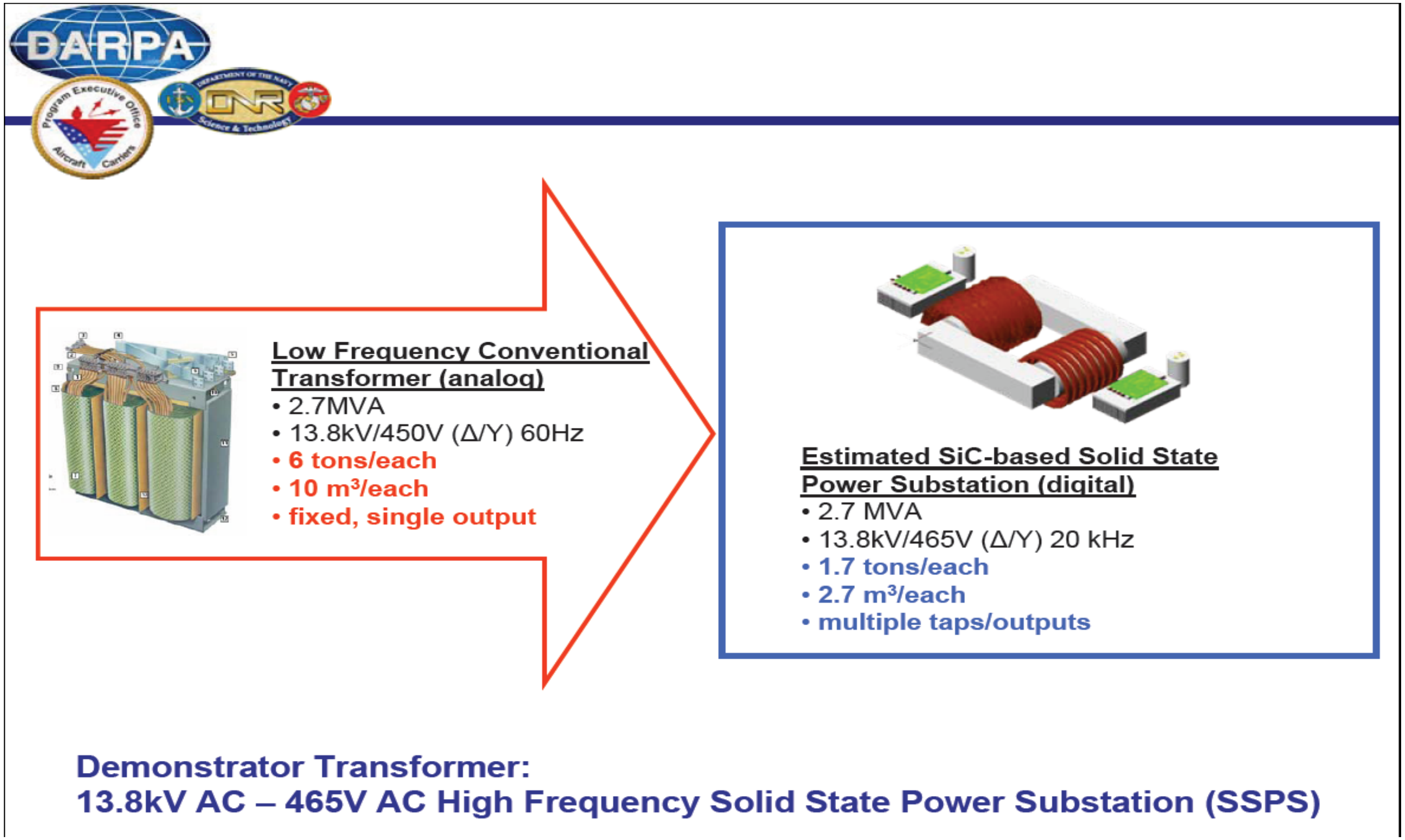
ONR

Revolutionary Research . . . Relevant Results

OFFICE OF NAVAL RESEARCH

# Solid-State Power Substation (SSPS) - Background

- Part of DARPA ‘High Power Electronics (HPE)’ program
- Objective – compact, light-weight power converters & transformers for US Navy enabled through high voltage SiC switches



# Solid-State Power Substation (SSPS)
## - DARPA 'High Power Electronics (HPE)' Program

| | |
|---|---|
| **GE Global Research** | System Design/ Integration, Component Characterization |
| CREE, POWEREX | SiC Devices/ Packaging |
| Los Alamos National Laboratory EST. 1943, IAP | High frequency Transformers |
| General Dynamics Electric Boat | Ship Integration Requirements |
| Virginia Tech, University of Wisconsin Madison | Modeling, Alternative architectures |

# High frequency transformers size reduction

220 kVA, 60 Hz
dry-type xfmr

330 kVA, 60 Hz
oil-filled xfmr
(1,220 kgs)

Oil-filled design, water-cooled
(45 kgs, IAP Research)

Dry-type design, forced air-cooled
(35 kgs, Los Alamos)

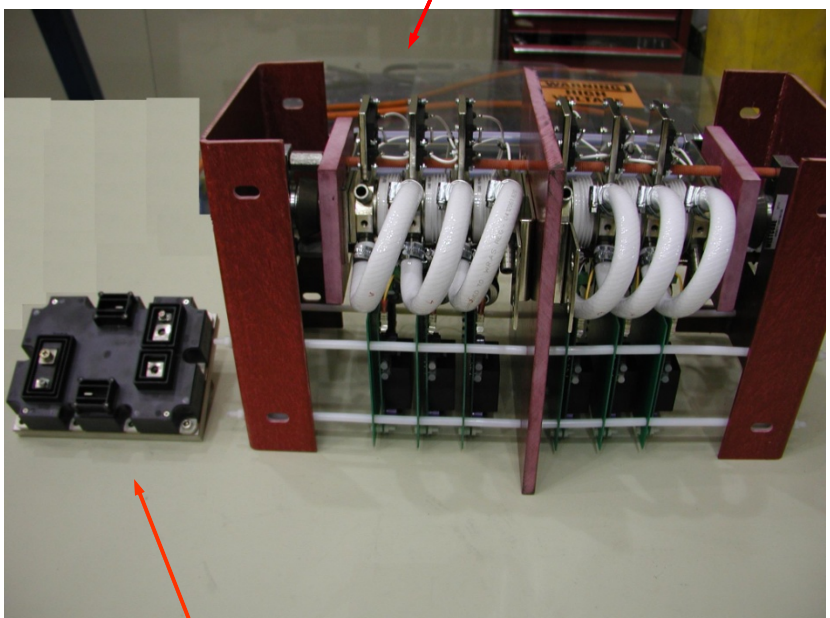
<u>250 kVA, 20 kHz transformers</u>

# SiC switches - size and performance benefits

**Si IGBT assembly, 10kV, 160 amps**

**(3x 4.5 kV devices in series)**

- **Conduction drop > 10 V**
- **Switching time > 3 ms**

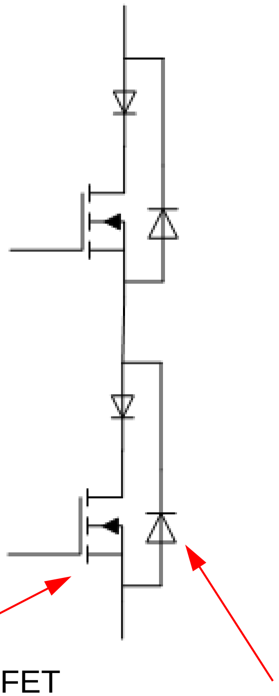


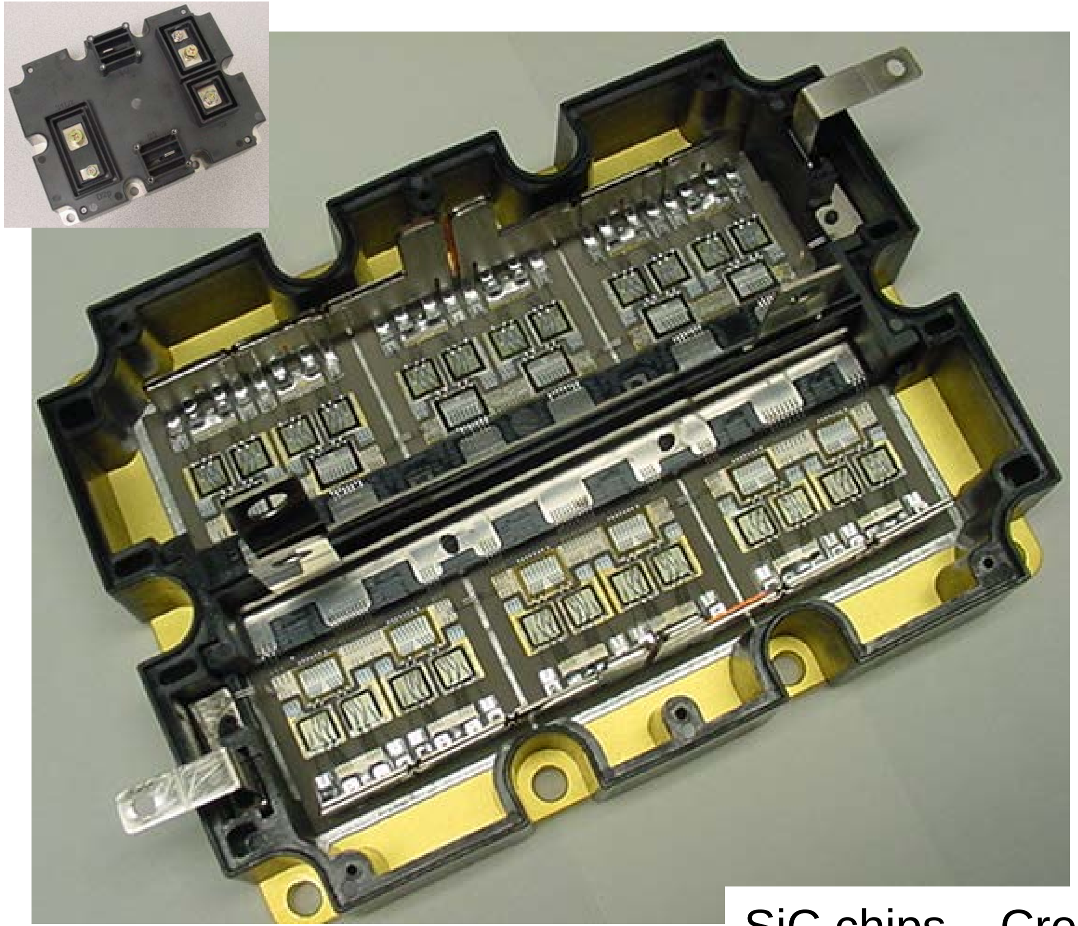

**SiC module, 10 kV, 120 amps (Cree, Powerex)**

- **Conduction drop < 6 V**
- **Switching time < 100 ns**

**SiC Module: turn-on/ turn-off @ 5kV, 100A**

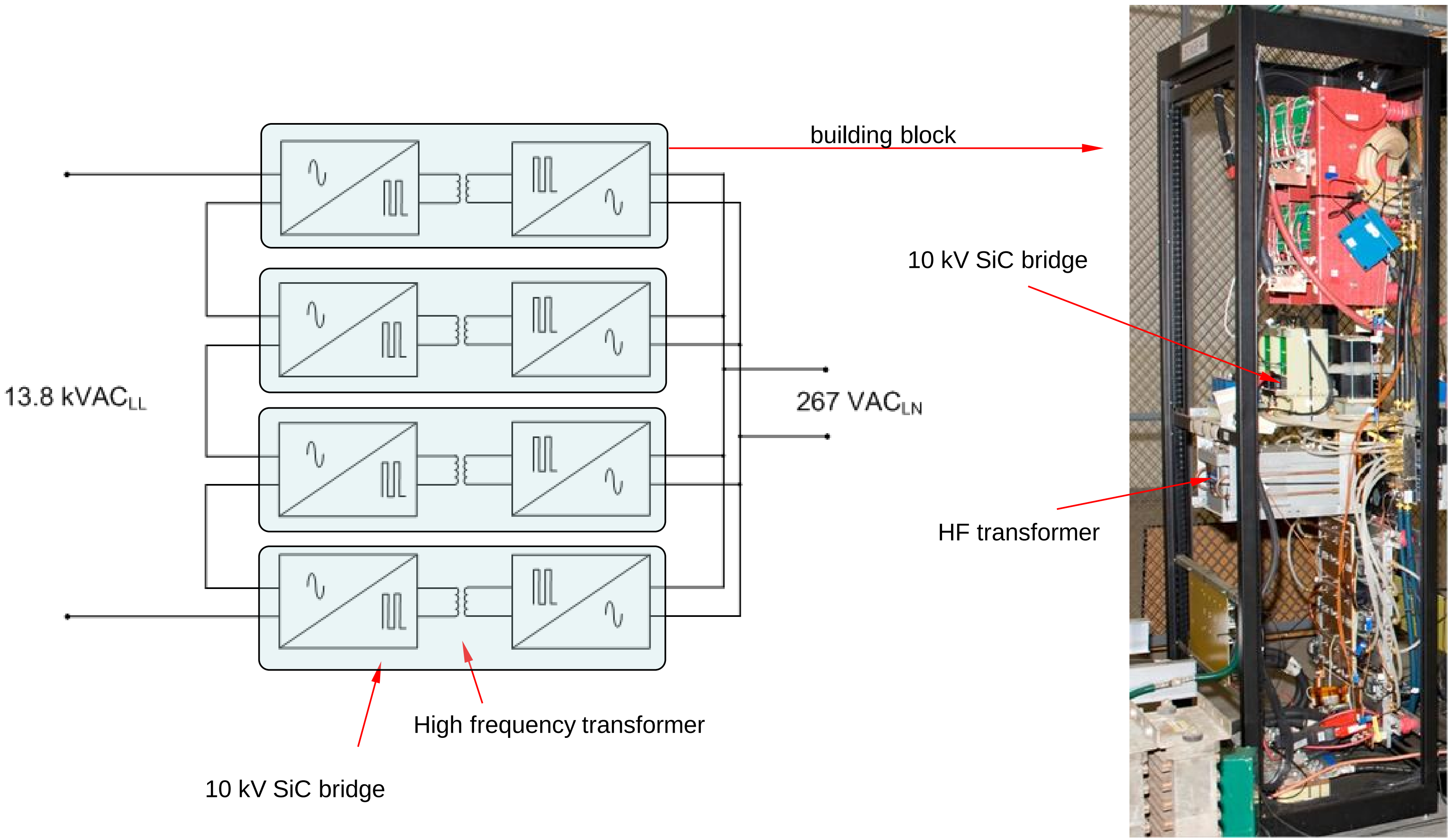
# 10 kV, 120 A Silicon carbide Half-Bridge Module



SiC chips – Cree
Module - Powerex

# SSPS - Prototype 250 kVA Building Block

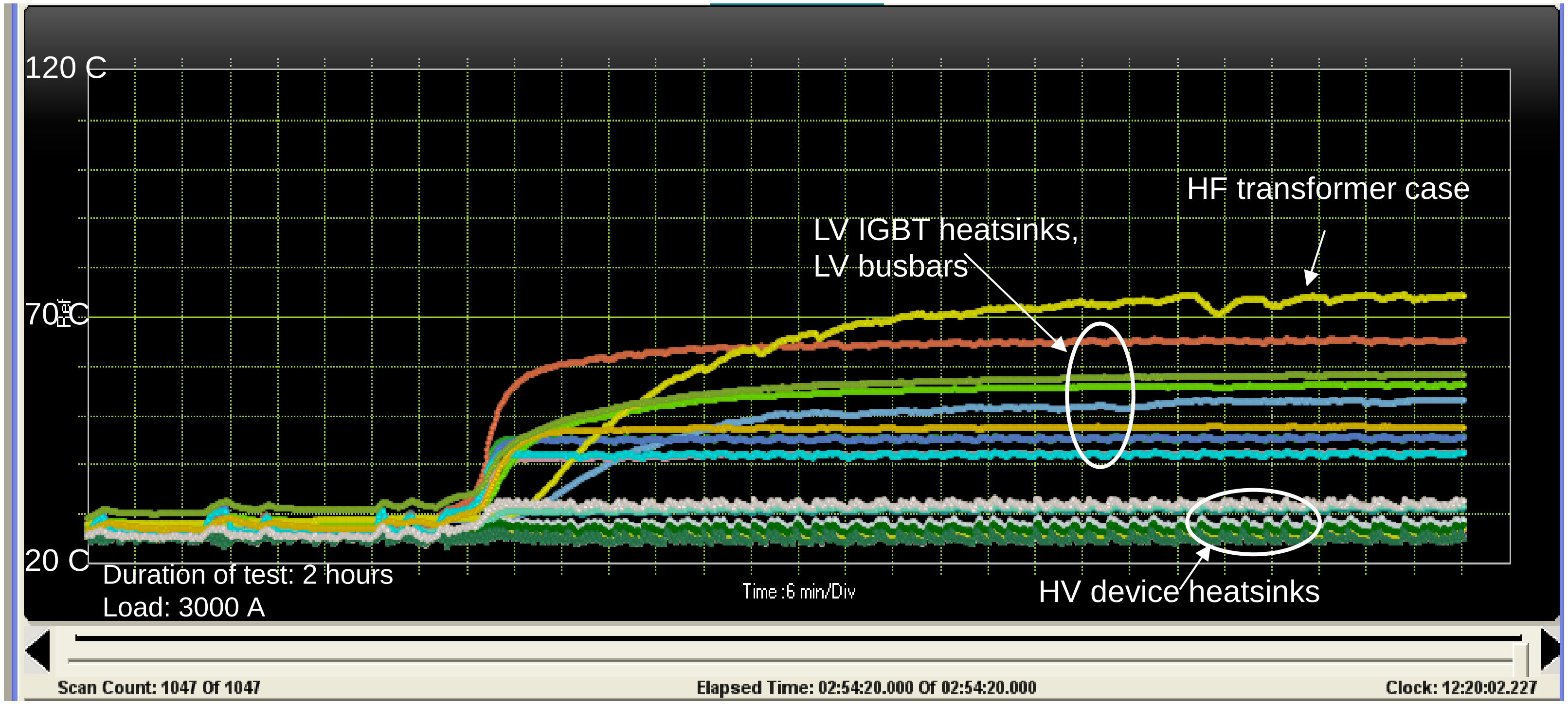


# SSPS 1 MVA Prototype Test Results

**Single-phase SSPS at Navy test lab**

- ✓ Demonstrated at 1 MVA, 13.8 kV/265 V
- ✓ Efficiency at full load > 97%
- ✓ 1/3rd weight of conventional transformer
- ✓ Clean 20 kHz waveforms
- ✓ Balanced sharing of voltages/ currents
- ✓ AC input current/ output voltage THD < 5%

# Thermal Measurements

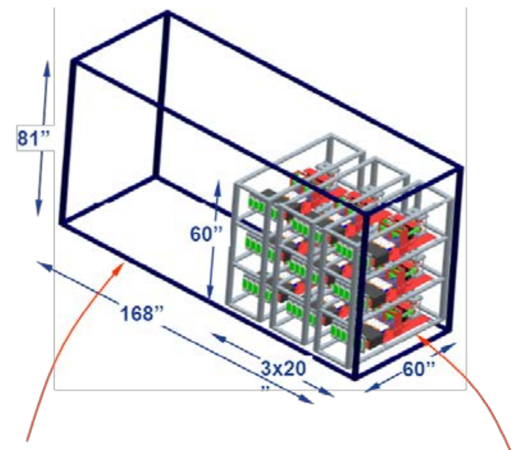



**SSPS temperature measurements – 2 hour load test**

- Inlet water – 25C
- SiC Modules – low temp rise
- Cooling of HF transformers and busbar/ connections is challenging

# HPE program - Ongoing Development

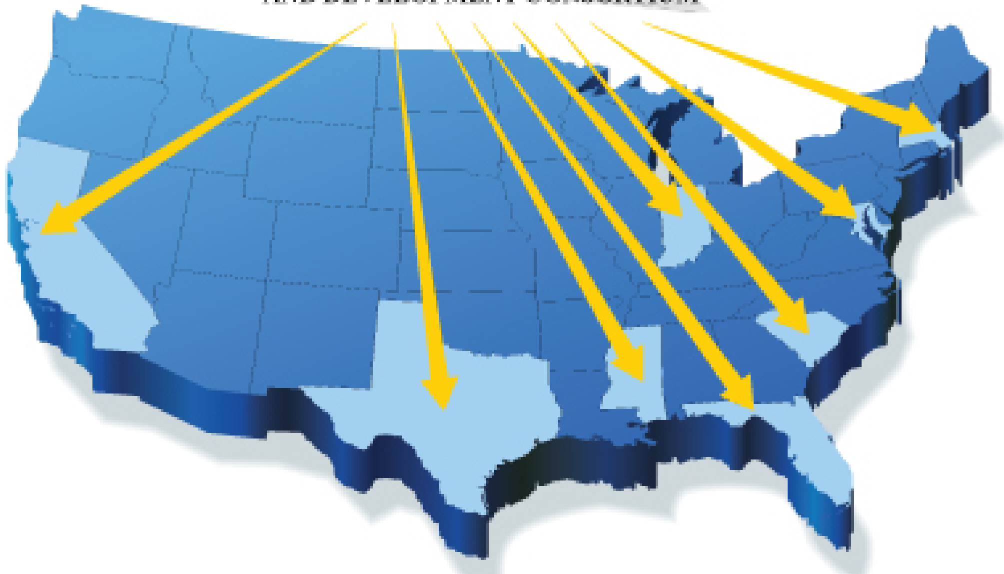
- Option Program
  - 1 MW, 4160Vac – 1000Vdc supply for AMDR radar,
  - TRL6 testing in Q4 2012
- 1/3rd volume, 1/10th weight of existing supply




Prototype under assembly

| | Present PCM-4 | SiC PCM-4/1A |
|---|---|---|
| Weight: | 35,000 lbs | 3,500 lbs |
| Volume: | 168”W x 60”D x 81”H | 60”W x 60”D x 60”H |

# Testing July 2012 – Real-Time Digital Simulation
# Power Hardware and Control hardware in the Loop Testing



# Potential Industry Applications

Renewables

- Enable power conversion and grid interface at higher voltage to reduce complexity and cost

Rail

- More efficient locomotive drives - reduce switching/diode recovery losses
- Compact transformers/electronics for catenary interface

T&D

- Reduce number of series devices needed to handle high voltage.
- HVDC/ FACTS converters with lower component count/ complexity
- Compact solid-state distribution transformers

  (smaller footprint, added functionality, oil-free)

# Challenges for high voltage SiC

- Cost – need market volume and higher yields
- Reliability - need validation from early adopters
- Limited current ratings for present devices/ modules
  - T&D, Drives, Wind applications will require higher ratings
  - Need large-area chips with good yields
- Development of supporting HV components – passives, gate drives, packaging, insulation, ..
- For HV applications, need to be cost-competitive compared with multilevel converters with LV silicon

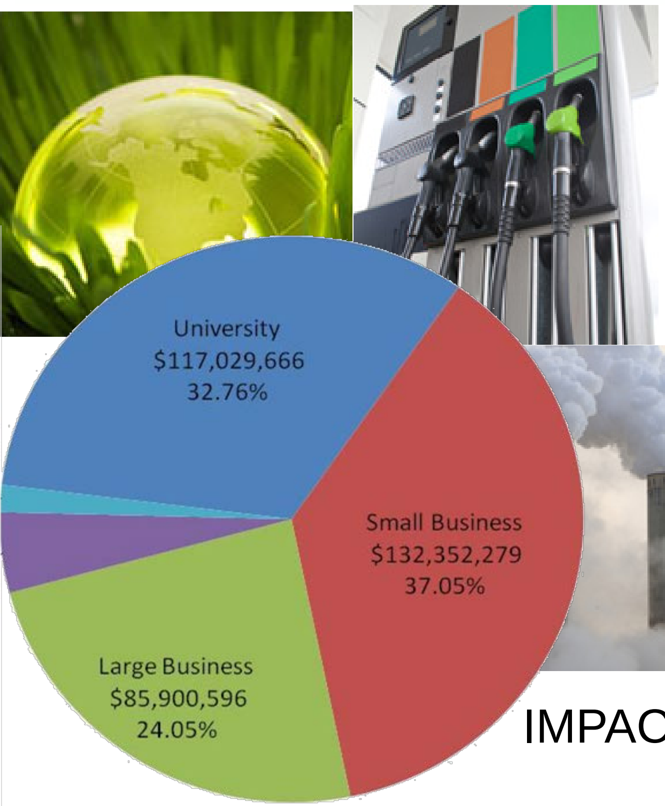

Pawel
Gradzki

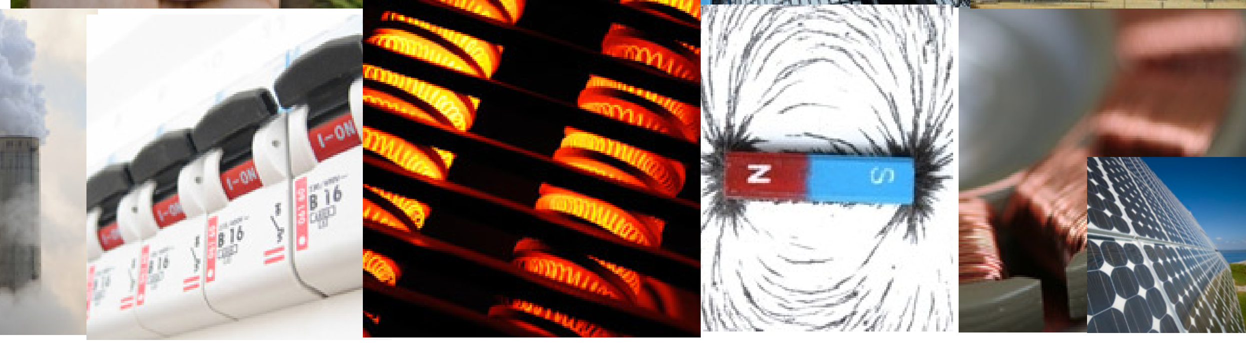
# Stimulating Energy Innovation

Rajeev Ram
Program Director
ARPA-E
Pawel Gradzki
Booz Allen Hamilton

# ARPA-E PORTFOLIO

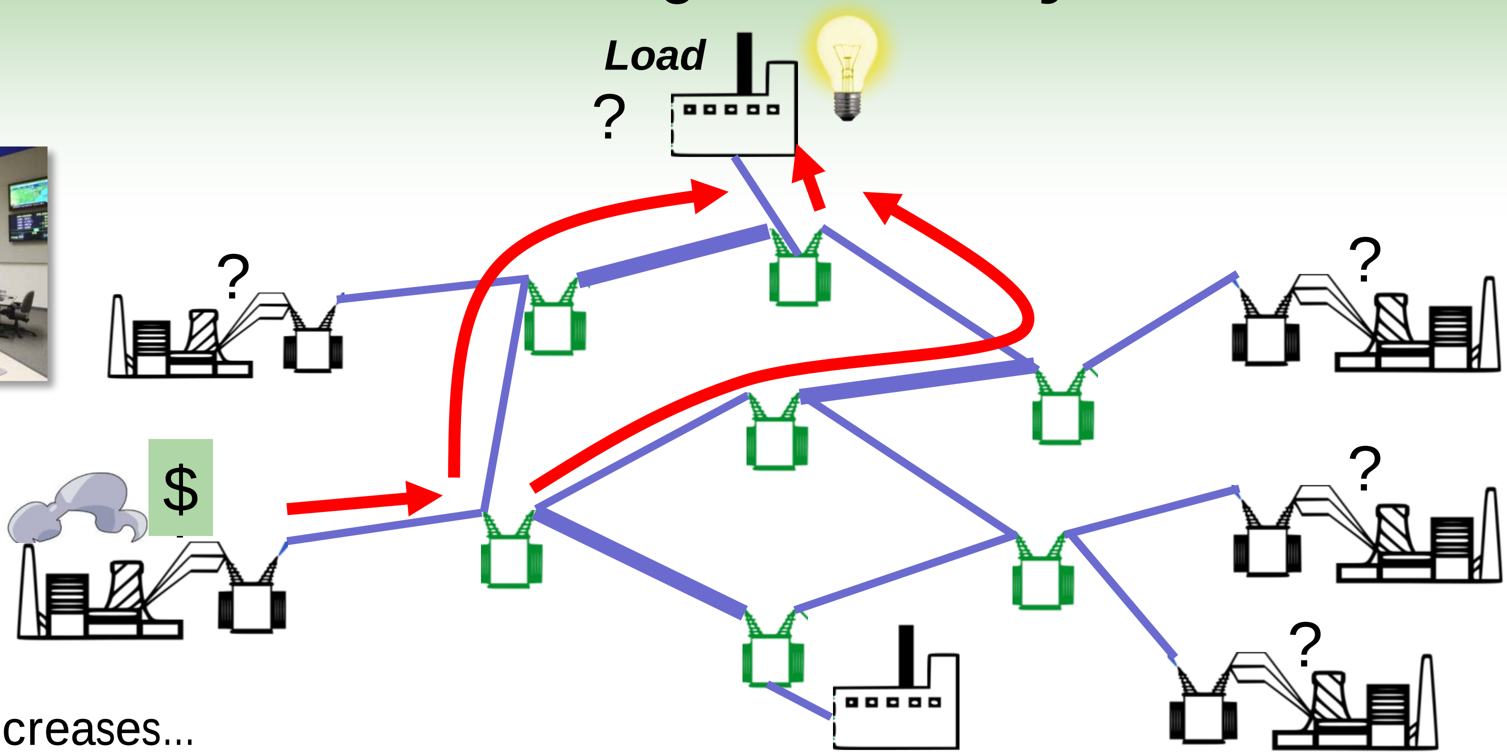
Broad Solicitation Electrofuels PETRO BEEST BEETIT GENI



IMPACCT GRIDS HEATS REACT ADEPT

# Delivering Electricity




As demand increases…

…day-ahead market & spot market coordinate additional generation

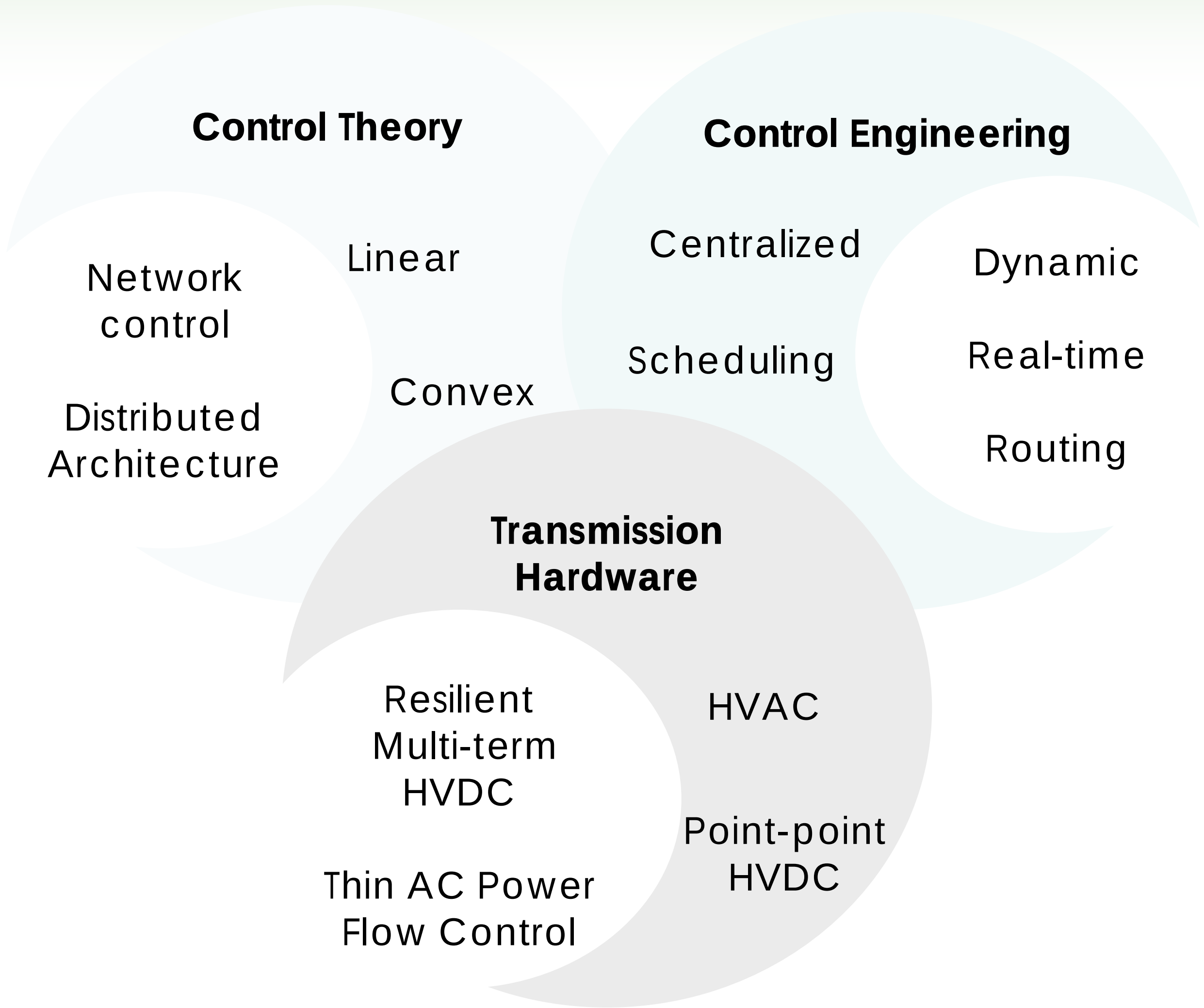
…generator spins up: coal/nuclear/gas (day-ahead), gas (spot market)

…power flows into the grid

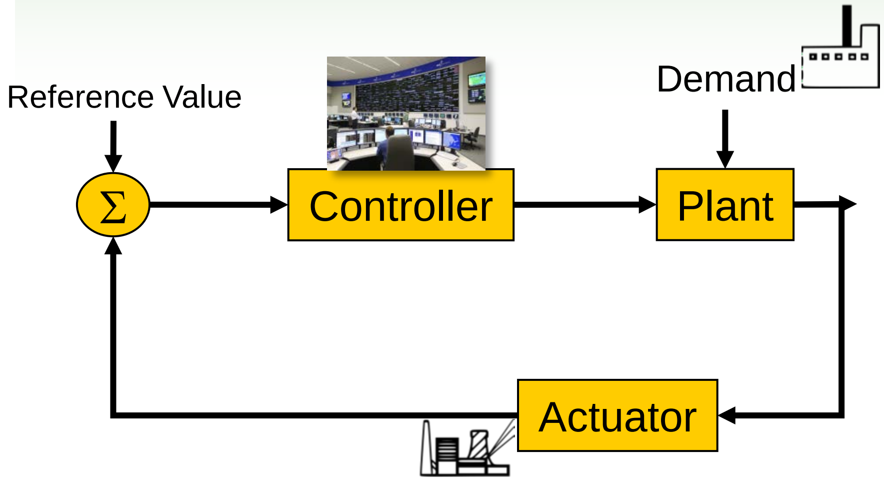
…electrons flow along path of least resistance

…the load draws power from the grid

# Workshops find the white space



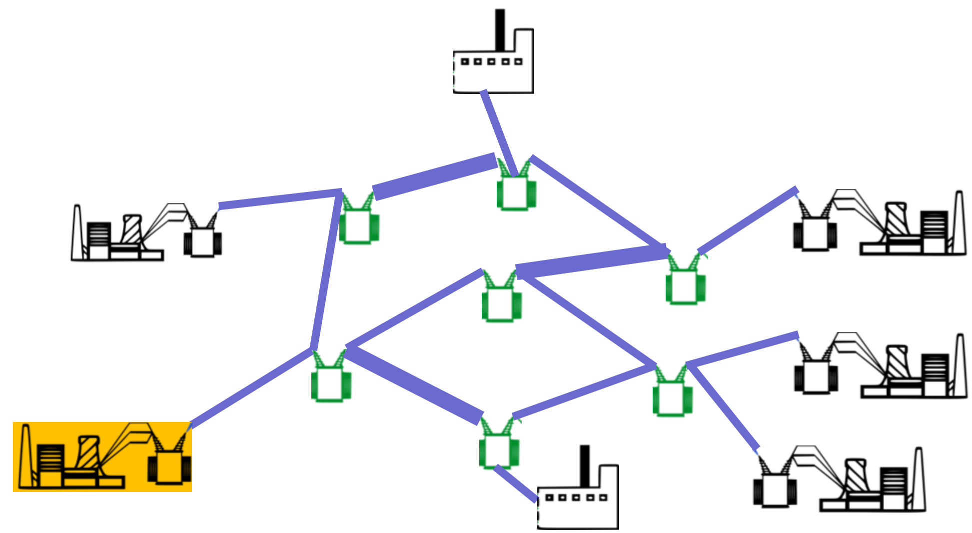
# Actuators




***Demand Response***

Schedule demand

(eg. large industrial loads)



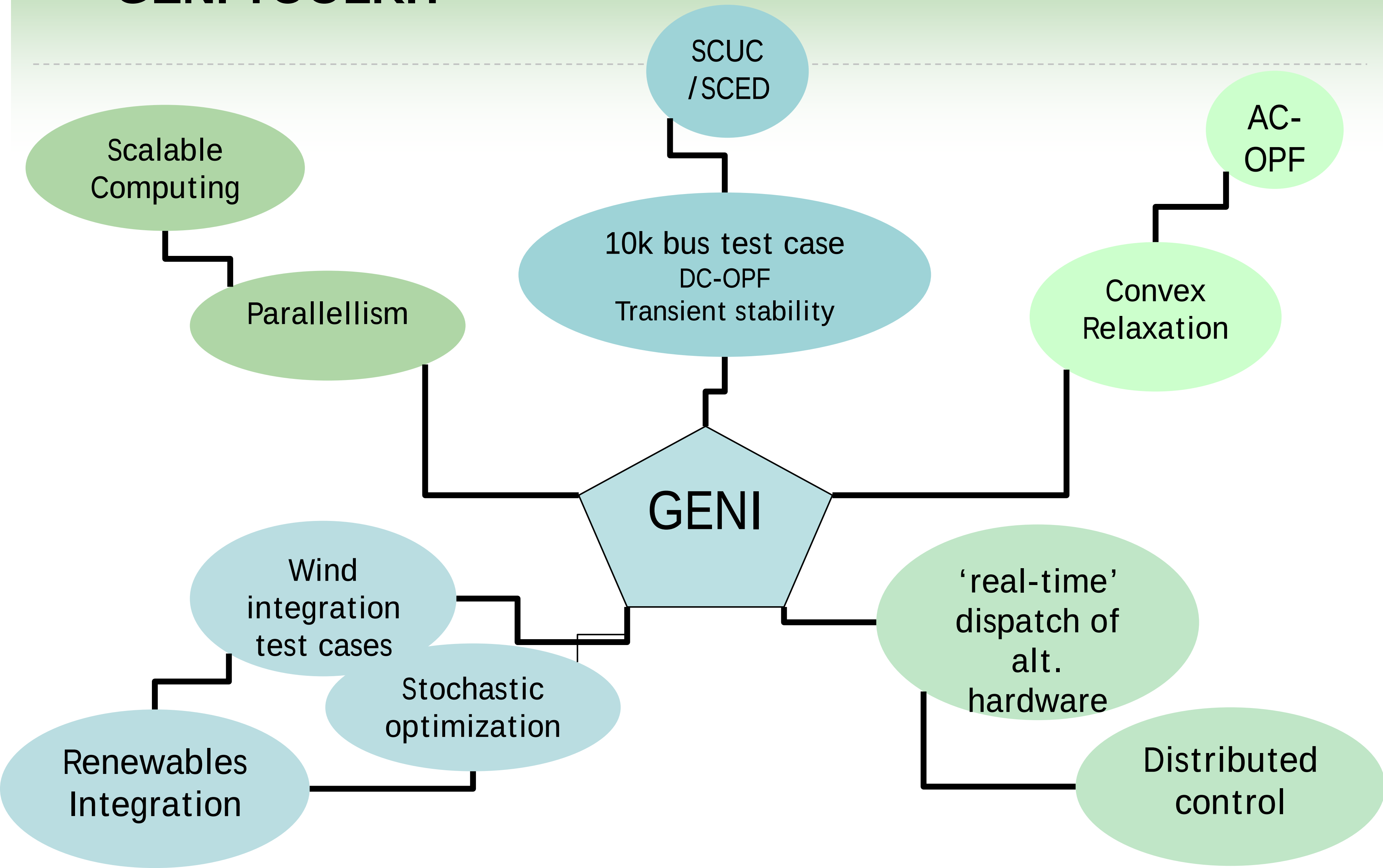
***Control in the Grid***

Flexible AC Transmission System

***Storage***

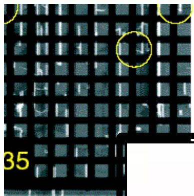
Make renewables dispatchable

# GENI TOOLKIT

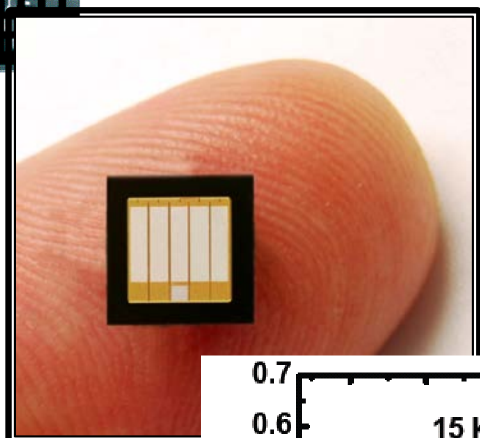


# Vertically Integrated Teams

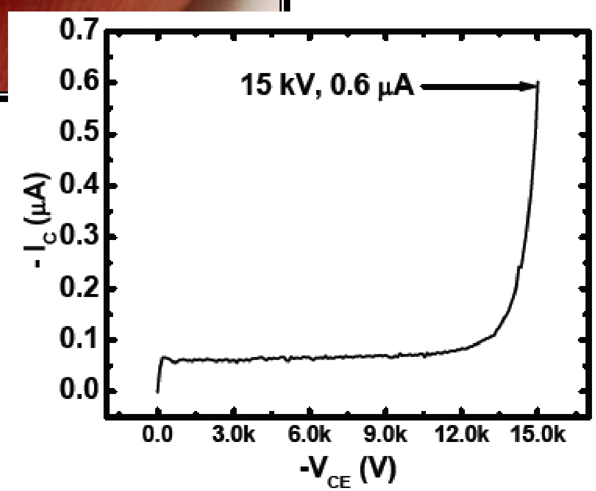
## HV Grid-Scale Transistors and Solid-State Transformers



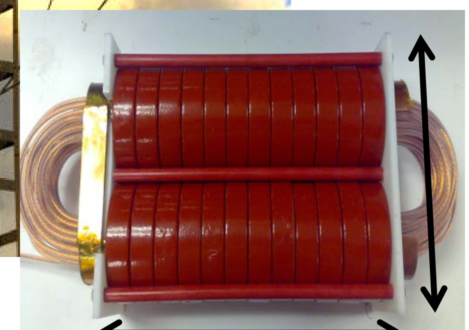

**NRL**



**Cree**




**NCSU**
**ABB**



17 cm

36 cm

***30kVA, 50kHz link transformer***

# GENI ARCHITECTURES FOR THE GRID

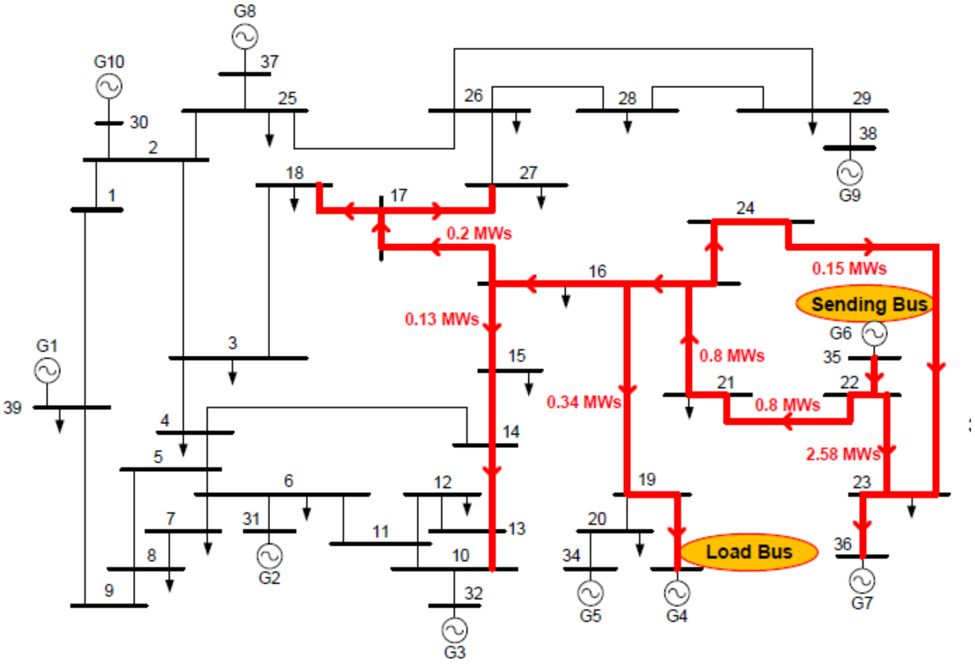
Routing electrical power

Mobilizing large numbers (100k) of small assets

# Benefits of Routing Power

*Today: Uncontrolled Flows*

*Power Routing*




•Power flow control to route power along underutilized paths, 80% less transmission infrastructure required

GA Tech study of simplified IEEE 39 Bus system with 4 control areas, operation simulated for 20 years, 20% RPS phased in over 20 years, sufficient transmission capacity added each year to eliminate curtailment of renewable generation

# TOPOLOGY CONTROL ALGORITHM

- Large size of most real-world power system models (~10k) in the US
- Large number of additional integer variables representing on/off line states
- Not separable
  power flow equations embedded in the optimization formulation

***<u>Example</u>***

ISO-NE: 689 generators, 2209 loads, 4500 bus, 6600 binary variables

Topology control (DC-OPF approx):

82 hrs [CPLEX on dual-core. 3.4GHz, 1GB RAM]

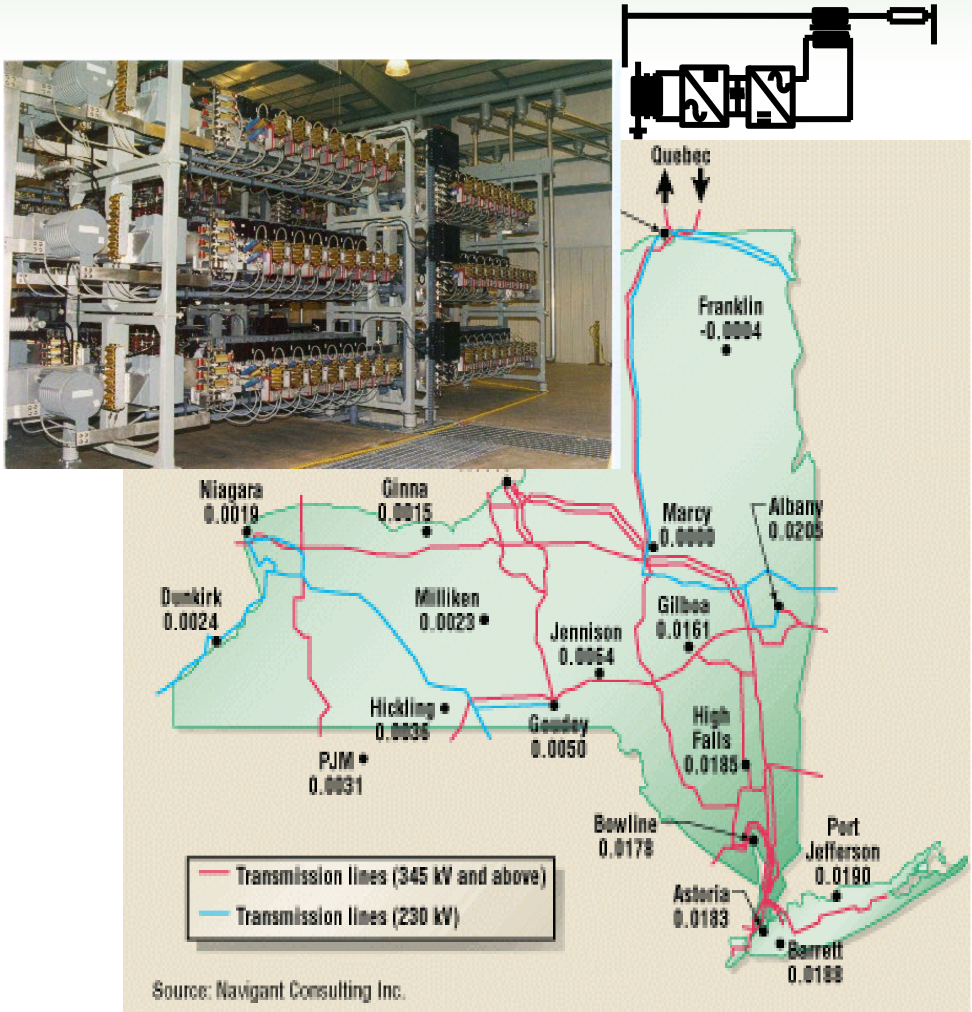
to optimize state **only 4** transmission lines

savings +5% for summer peak conditions / + 7% for a medium load summer condition

*Hedman, K. W., O'Neill, R. P., Fisher, E. B., and Oren, S. S. (2011), "Smart flexible just-in-time transmission and flowgate bidding," IEEE Transactions on Power Systems,Feb 2011.*

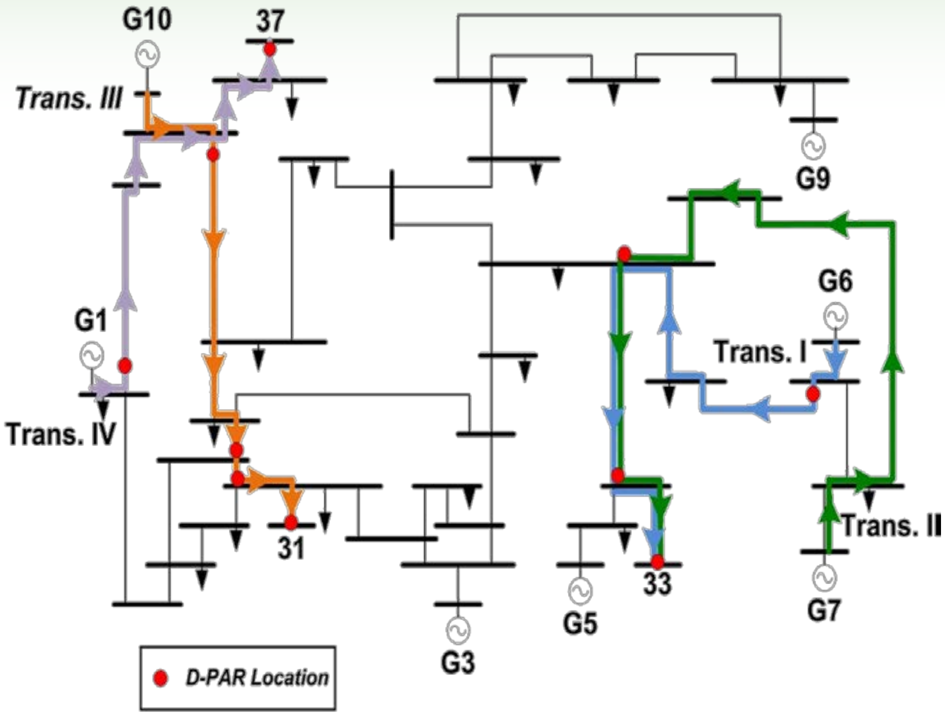
# ROUTING POWER TODAY

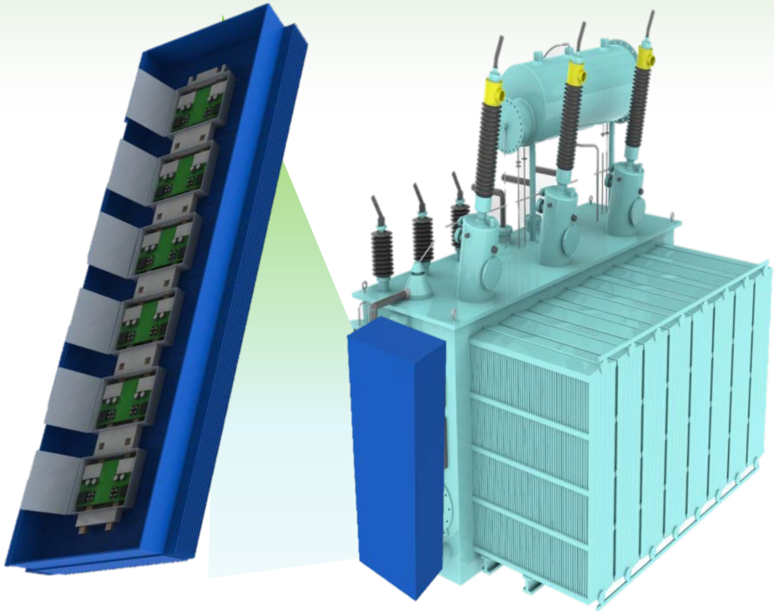
## Utility: AC Univesal Power Flow Controller




# Vertically Integrated Teams

## Power Routers



*augment existing transformers*

Varentec EPRI

Georgia Tech

WAUKESHA® TRANSFORMERS • SERVICE TRAINING • COMPONENTS

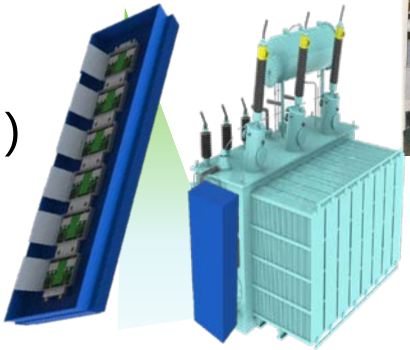
- 10X lower than BAU ($30/kW)
- 13 kV/1MW units in tie-line field demo
- 13 kV 5 bus test bed to show routing

SOUTHERN COMPANY

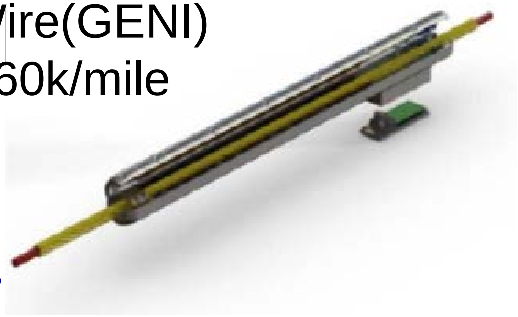
# ARPAE PROGRAMS DEFINE PROBLEMS…
# …NOT SOLUTIONS

*NYPA UPFC*

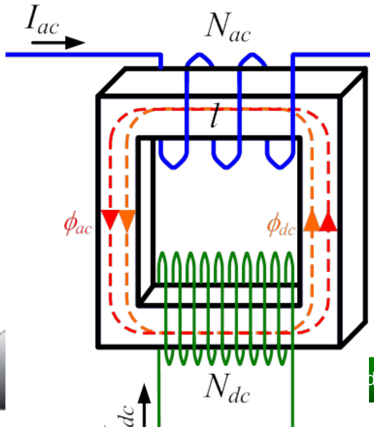
$140-300/kVA



Varentec (GENI)
$20-30/kVA



SmartWire(GENI)
$36k-60k/mile

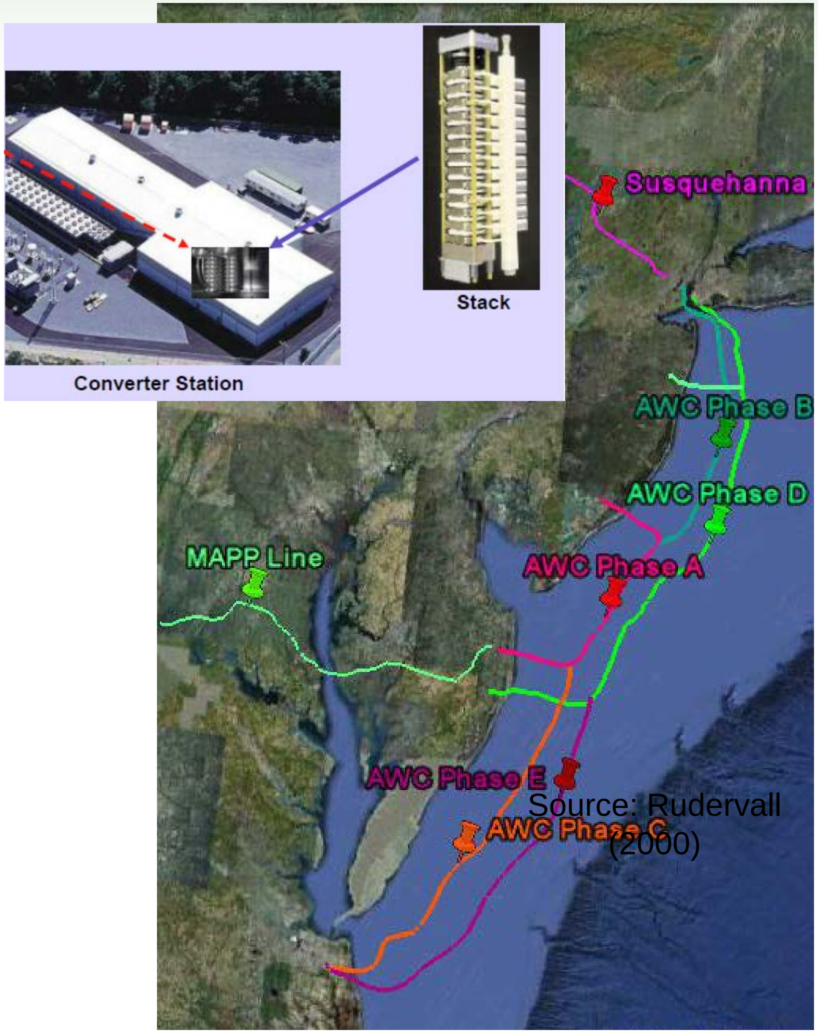


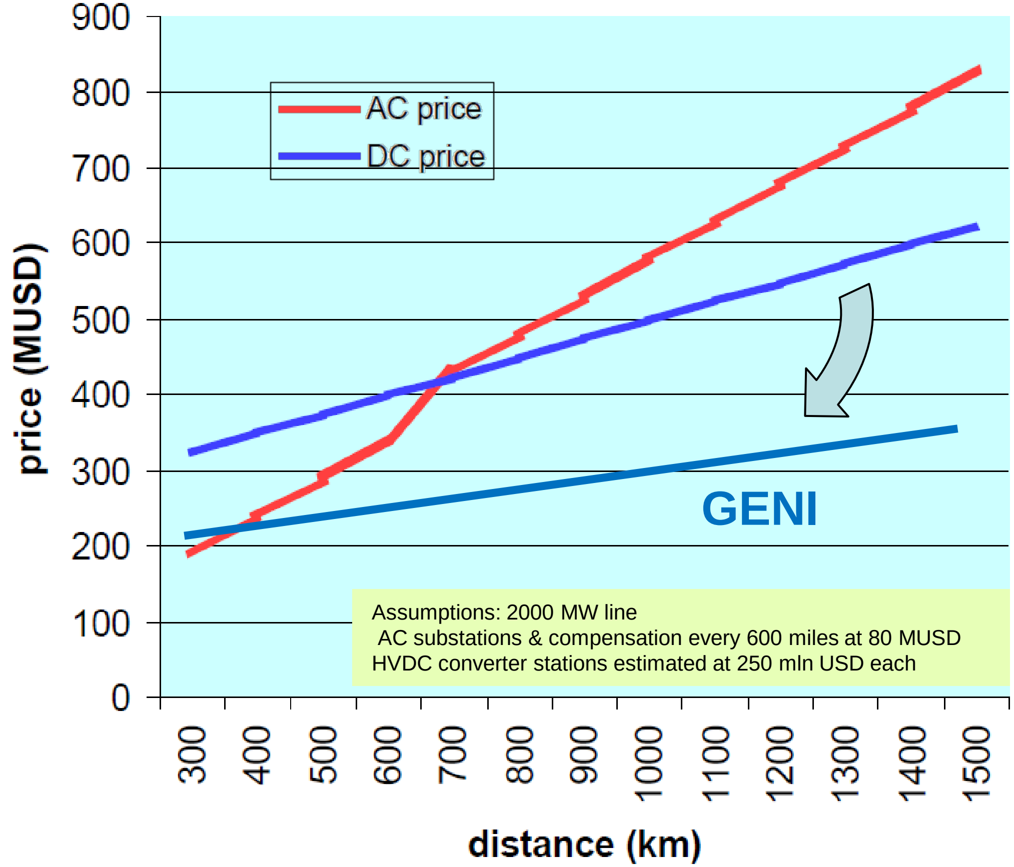

ORNL (GENI)
$4/kVA

**A PORTFOLIO OF APPROACHES**

# ROUTING POWER TODAY

## Multiterminal HVDC



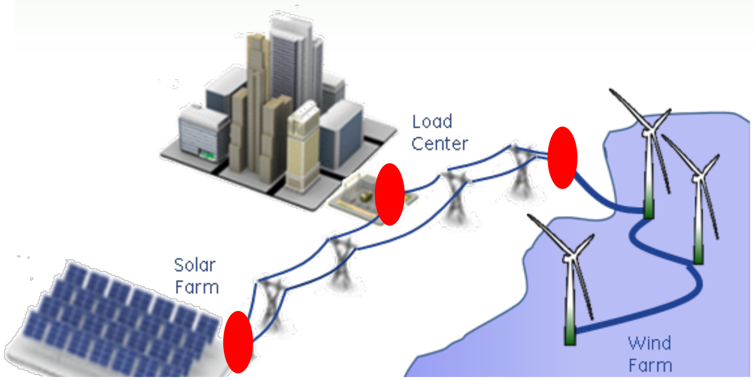



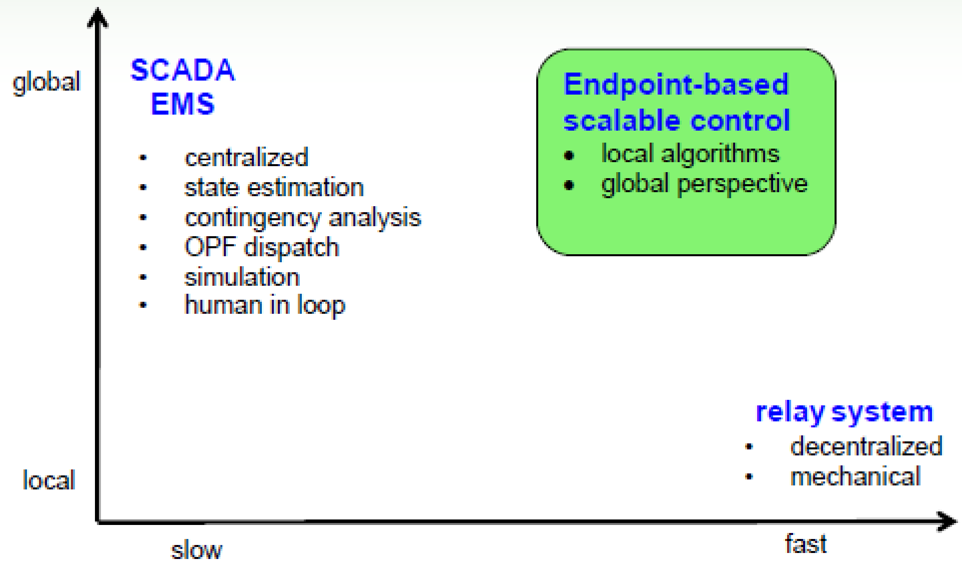
# GENI ARCHITECTURES FOR THE GRID

Routing electrical power

Mobilizing large numbers (100k) of small assets

# Scalable real-time decentralized Volt/VAR control




## Key Innovations

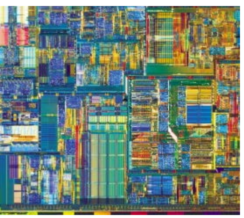
- Distributed control through local sensing, computation, and communication, yet jointly optimize certain global objectives
- ***Characterize AC-OPF subproblems that are polynomial-time solvable***
- Propose a new approach to solve OPF
- 100k inverters for Volt/VAR control

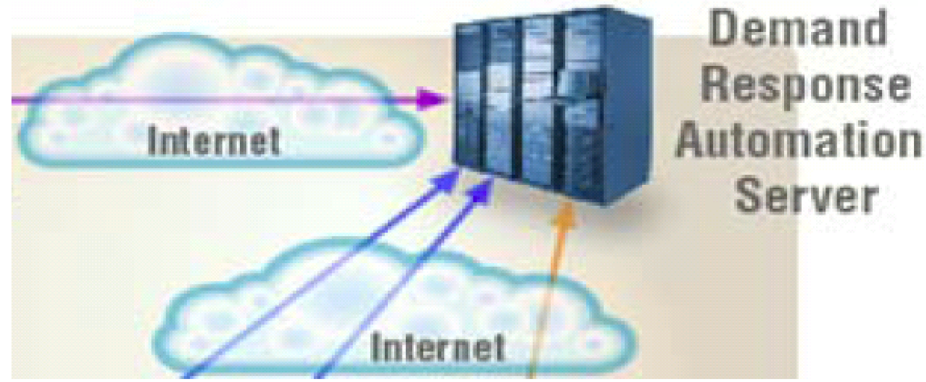
# Vertically Integrated Teams
## Algorithms for Topology Control

| | |
|---|---|
| Charles River Associates | Project management, algorithms, impact assessments, integration, commercialization |
| Boston University | Optimization algorithms, market design issues |
| Tufts University/ Northeastern University | Express algorithms for voltage and transient stability analysis |
| Polaris Systems Opt./ Paragon Decision Technology | Software implementation |
| PJM Interconnection | Operation and implementation consulting and review |

Estimates indicate that implementation of TC in the entire US electrical grid would save of $1-2 billion in generation costs and would reduce the needs for transmission investments

# STIMULATING INNOVATION FROM ADJACENT FIELDS

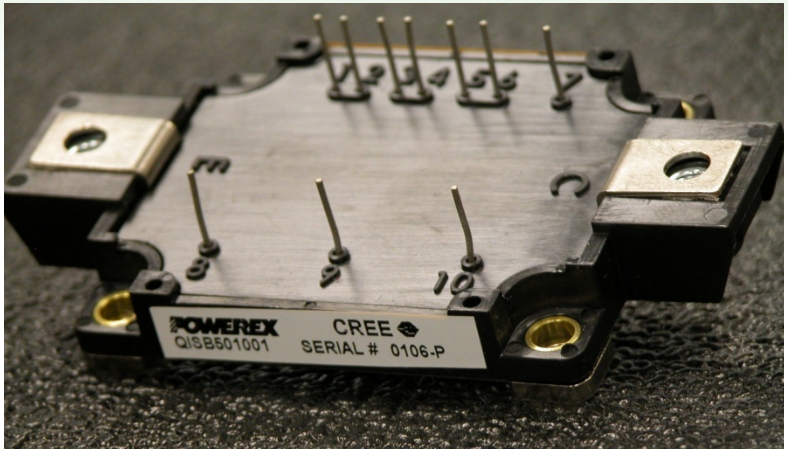




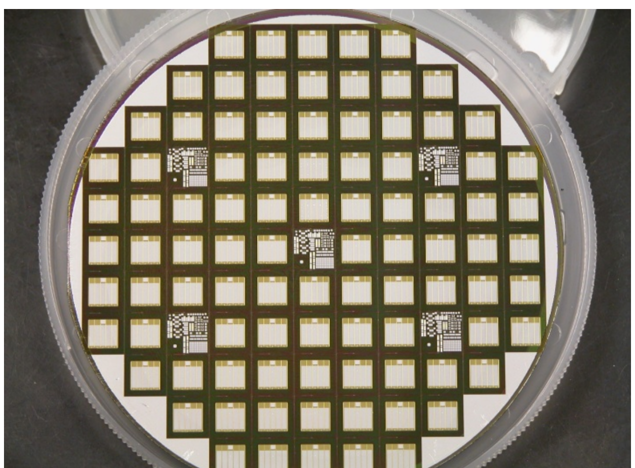

OpenADR, low-cost, internet-protocol based telemetry solutions, and intelligent forecasting and optimization techniques to provide "personalized" dynamic price signals to *millions* of customers in timeframes suitable for providing ancillary services to the grid

# Grid Scale Electronics

## Cree, NRL, NCSU, ABB

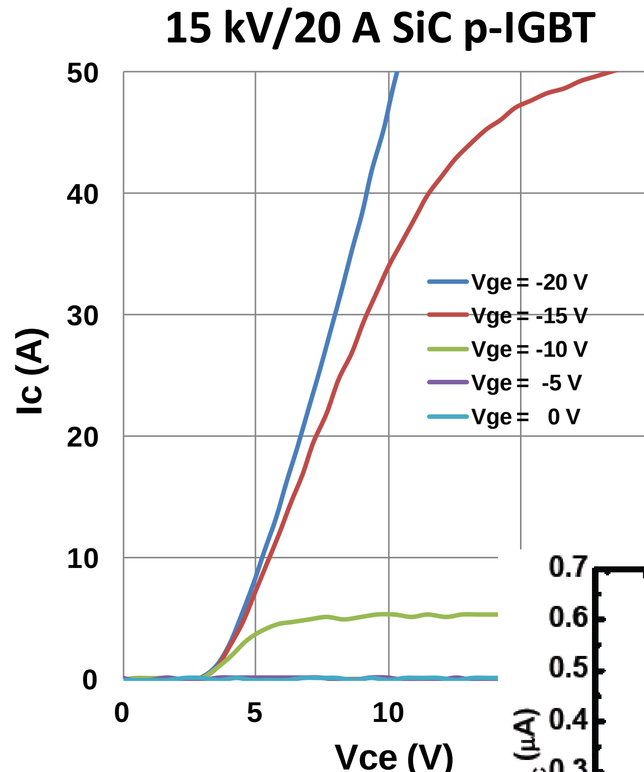


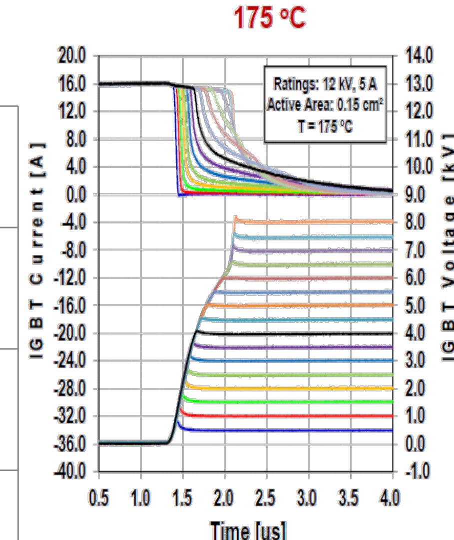

• 15 kV SiC IGBT Switch Module – World's Highest Voltage Semiconductor Switch

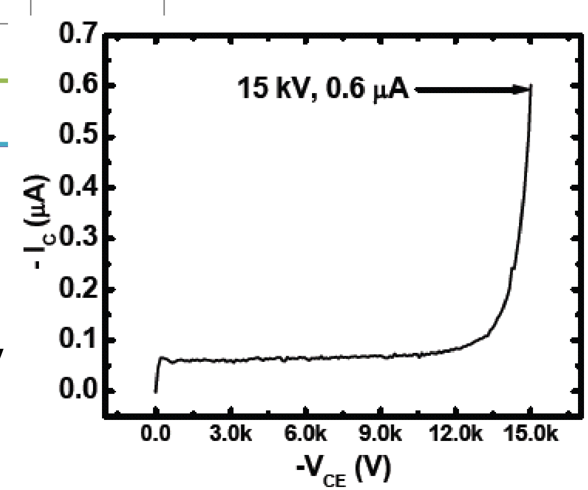


• 15 kV/10 A SiC p-IGBTs Fabricated On 100 mm 4HN-SiC Wafer

• Developed **15 kV SiC IGBT – World's Highest Voltage Semiconductor Switch**



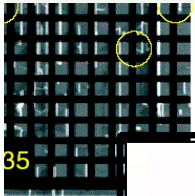




• **15 kV/20 A SiC p-IGBT**

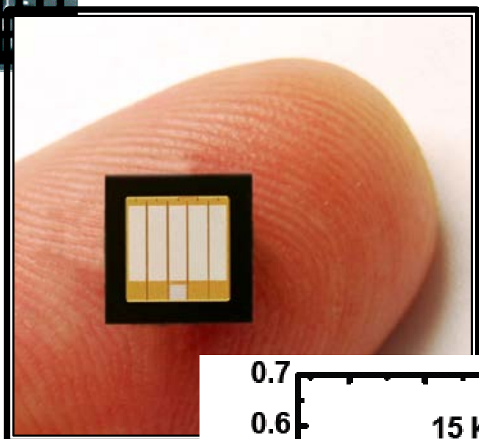
• $V_F$ = 6.5 V @ 20 A, $V_{GE}$ = 20V

• State-of-the-Art SiC p-IGBT Developed Under ARPA-E ADEPT Program

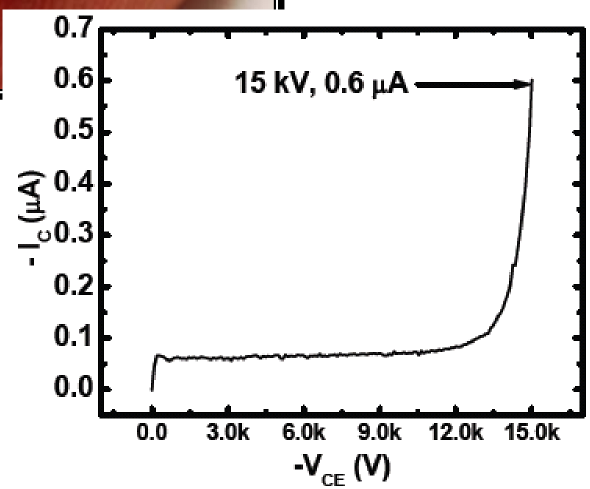
# HV Grid-Scale Transistors and Solid-State Transformers

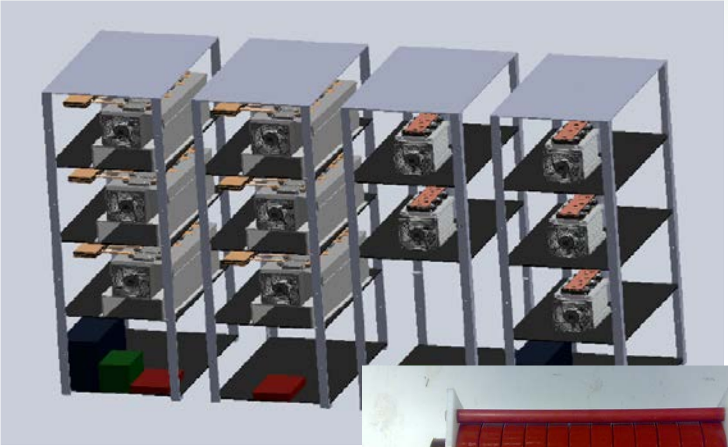



NRL

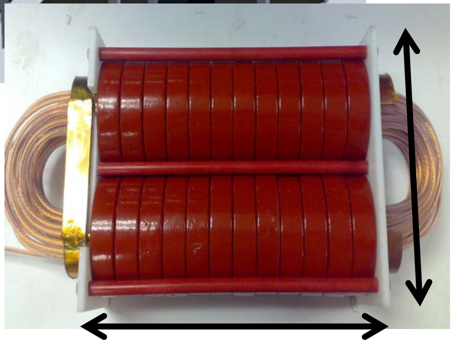


Cree



NCSU



17 cm

36 cm

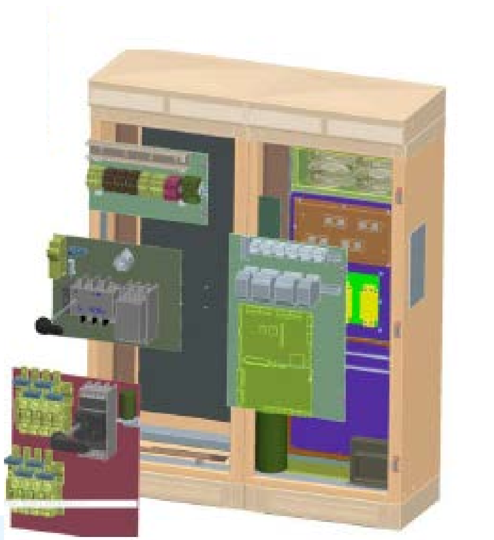
***30kVA, 50kHz link transformer***

# SOLAR ADEPT TARGETS

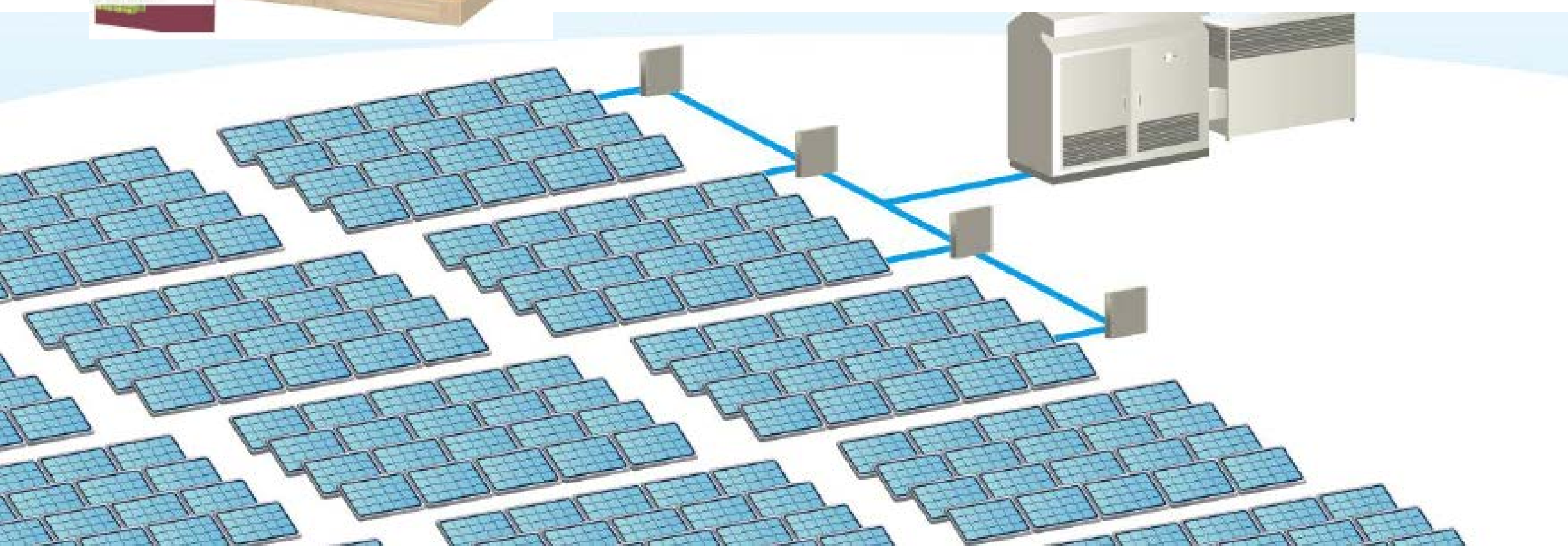
| System Categories | Cost | Voltage & Power | CEC Efficiency | Size |
|---|---|---|---|---|
| Category 1 **Sub-module converter (Smart bypass)** | $0.05/W | >3 converters /module | >98% cell-to-AC MPPT | Single-chip DC/DC Inside Module Frame |
| Category 2 **Microinverter (Residential)** | $0.20/W | >600 V >250 W | >98% cell-to-AC | < 2 lbs Integrated: < 10 parts |
| Category 3 **Lightweight (Commercial)** | <$0.10/W | 100kW | >98% cell-to-AC MPPT | < 50 lbs |
| Category 4 **Utility-scale Converters** | $0.10/W | > 2 MW scalable | >98% module-to-grid | < 1000 lbs |

# UTILITY SCALE INVERTER

<u>*1MW Photovoltaic Inverter*</u>

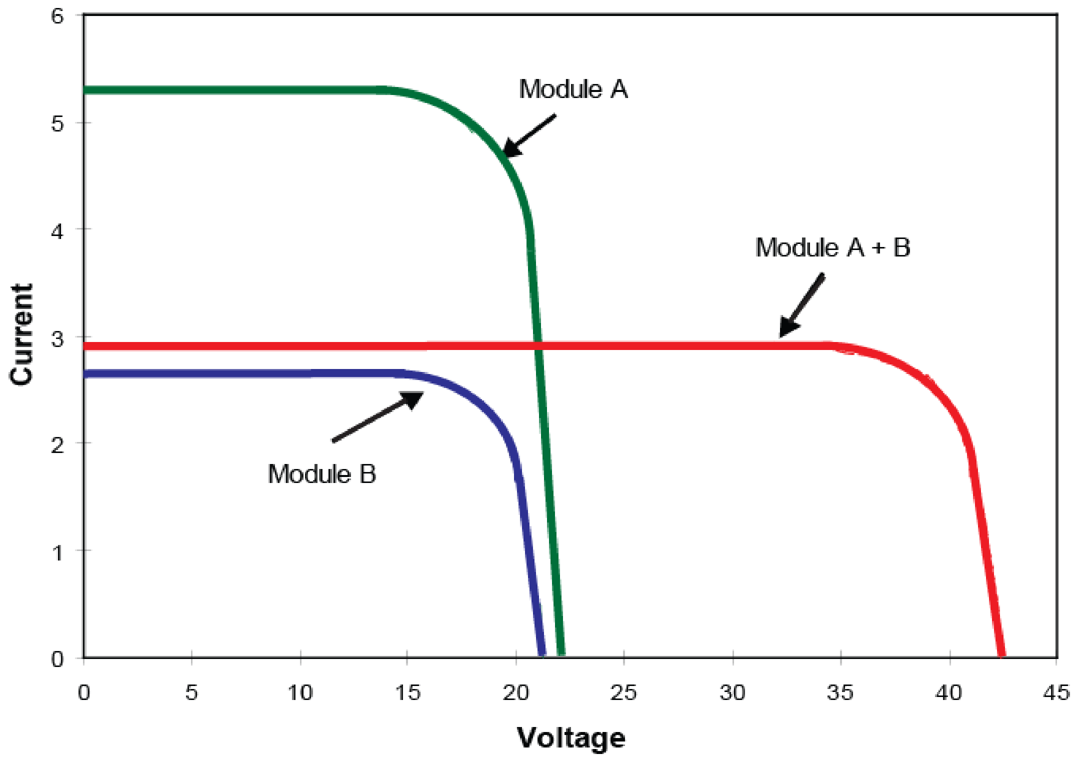


- Weight 10,000 lbs
- Modular from 50 kW – 1 MW
- Si IGBT (motor parts)
- 30% cost magnetics (steel & copper)
- $0.2/W (in China $0.17/W)
- 10 yr life (20 yr extended warranty)
- >500kW (approx annual sales 1k units)



U.S. DEPARTMENT OF ENERGY

# DISSIMILAR MODULES IN SERIES



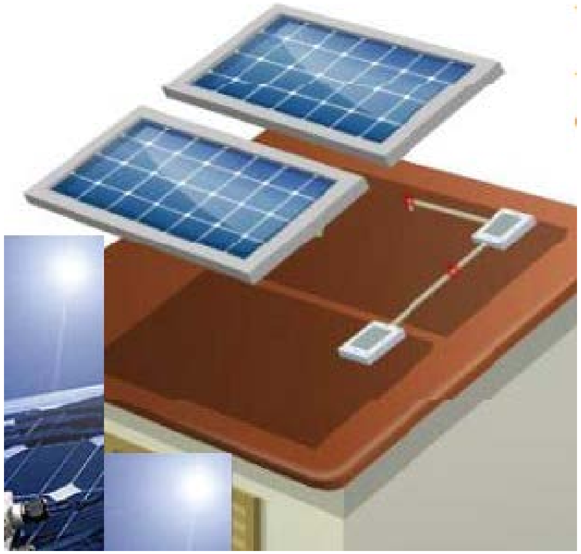

| Shade | Power Loss Series Connection |
|---|---|
| 0.15% | 3.7% |
| 2.6% | 16.7% |

# MICROINVERTERS


Barriers to adoption:

- Cost to Install
- Risk Averse Customers
- Cost to Maintain/Repair
  (multiple point of failure)





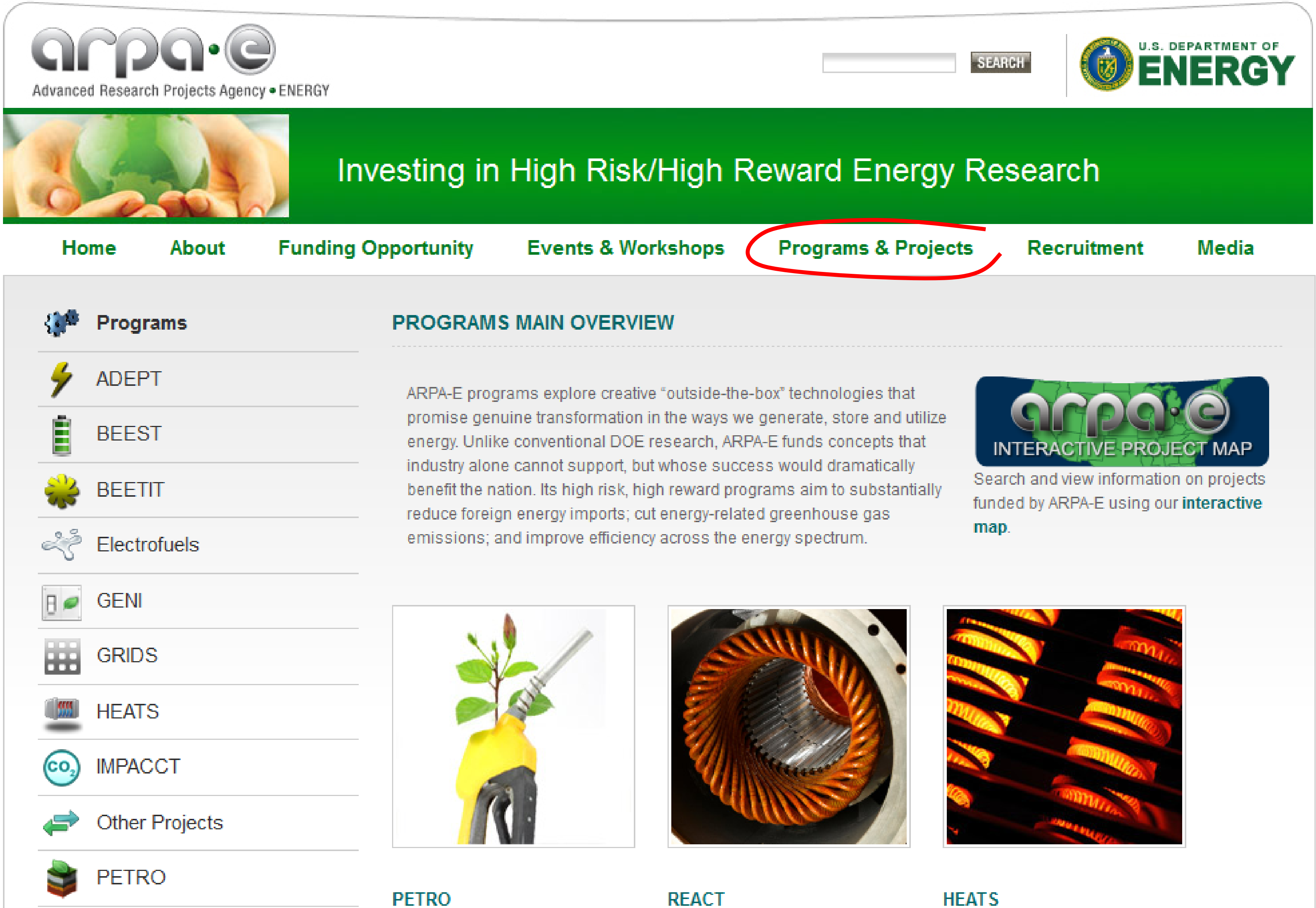
# MULTISTAGE INVERTER

**BASE CASE**


**1/10 the weight , 1/3 lower losses, ½ the manufacturing cost**

| | Power (Watt) | Weight (lbs) | Lbs/kW | CEC Efficiency | Est. Mfg Cost |
|---|---|---|---|---|---|
| PVPowered | 35K | 1200 | 34 | 95.5% | $10K |
| SatCon Power Systems | 30K | 1204 | 40 | 95.0% | $10K |
| IDEAL POWER CONVERTERS | **30K** | **80** | **2.7** | **97.0%** | **<$5K** |

Hi-voltage switches and hi-frequency transformer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GRIDS
HEATS
IMPACCT
Other Projects
PETRO
PROGRAMS MAIN OVERVIEW
ARPA-E programs explore creative "outside-the-box" technologies that promise genuine transformation in the ways we generate, store and utilize energy. Unlike conventional DOE research, ARPA-E funds concepts that industry alone cannot support, but whose success would dramatically benefit the nation. Its high risk, high reward programs aim to substantially reduce foreign energy imports; cut energy-related greenhouse gas emissions; and improve efficiency across the energy spectrum.
INTERACTIVE PROJECT MAP
Search and view information on projects funded by ARPA-E using our interactive map.
PETRO
REACT
HEATS

Leo

Casey

# Discussion

- Applications Requirements: Control, Integration and control of renewables and storage. Microgrids , congestion relief, supply and demand response. Distribution Automation.
- Stakeholders: Power producers, ISOs, grid operators, utilities, power electronic equipment manufacturers, energy and power generation/storage manufacturers. (related stakeholders also include regulators, safety/standards bodies, rate payers, investors) & Government.
- System Performance Issues: Cost, efficiency, reliability, overload, fault behavior. Advantages and possibilities
- Technical barriers/issues: Controls, communications, anti-islanding, lvrt, optimization (device, site, system,… ), EPC, Simulation,
- Hardware Issues – What are the gaps in terms of devices, systems, integration,
- Technology Demonstration Issues (Modeling, Demo)
- Technologies, scale, number

**Progress made to date**

**Potential**

**Plans-Maps-Gaps**

**Risk Aversion – Adoption**

**Rugged, Square SOA**

# Applications Requirements:

Control of voltage, power-factor and faults through solid-state devices.

Integration and control of renewables and storage.

Seamless isolation from grid outages and disturbances through microgrids.

Ability to relieve congestion.

Achieve improved demand and supply response.

-speed?

-strengths and weaknesses?

-needs?

-differences from E/M

-devices, solid state, other

## Stakeholders:

- Power producers, ISOs, grid operators, utilities, power electronic equipment manufacturers, energy and power generation/storage manufacturers.  (related stakeholders also include regulators, safety/standards bodies, rate payers, investors)

-do we have a full discussion?
-can we leverage other issues?

# System Performance Issues:

- a. Cost, efficiency, reliability, Temperature rating, RBSOA, overload, fault behavior
- b. Advantages and possibilities

-5% or 15%?
-”core” cost at high power is ~30%

-Sunshot goals? (10c/W)

**Technical barriers/issues:**

a. Controls, communications, anti-islanding, lvrt, optimization (device, site, system,… )

b. EPC

c. Simulation

**Hardware Issues:**

-What are the gaps in terms of devices, systems, integration?

**Technology Demonstration Issues:**

**Technologies, scale, number:**

**Commercial Penetration:**