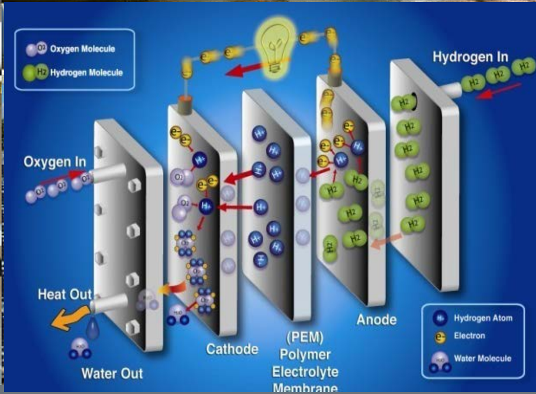
# Opportunities for Wide Bandgap Semiconductor Power Electronics for Hydrogen and Fuel Cell Applications

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy





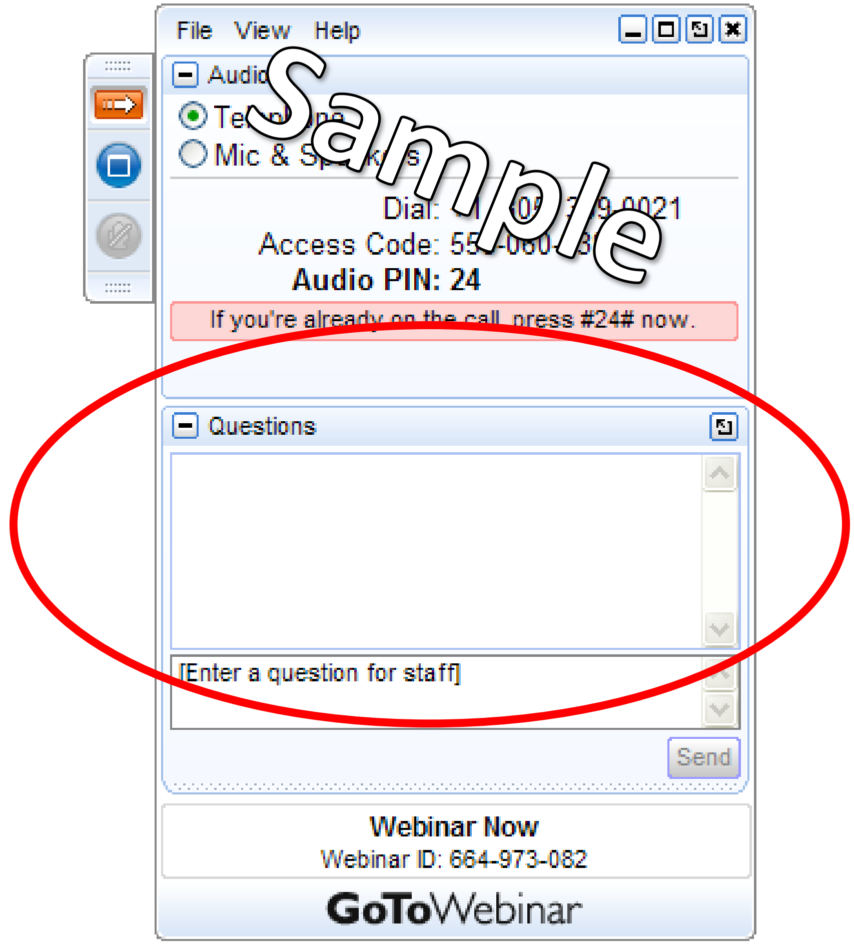

Presenters:
Jeff Casady and John Palmour of Cree Inc.

DOE Hosts:
Eric Miller and Anant Agarwal

U.S. Department of Energy
Fuel Cell Technologies Office

# Question and Answer

- Please type your question into the question box



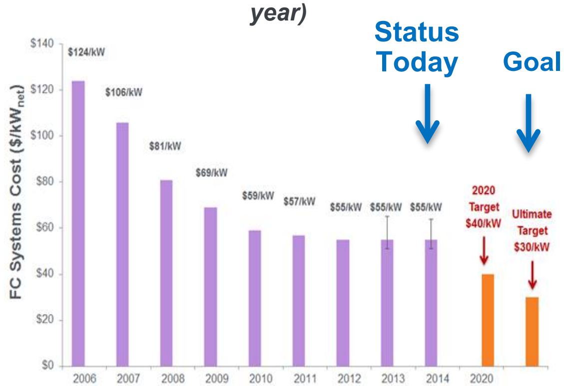
# DOE Fuel Cell Technologies Office covers Research, Development, Demonstration & Deployment

**FCTO Website: http://energy.gov/eere/fuelcells/fuel-cell-technologies-office**

## DOE R&D

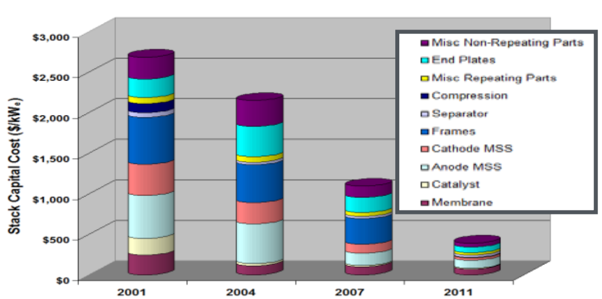
### Fuel Cell System Cost

*Transportation projected to (500,000 units per year)*




***50% reduction vs. 2006 ($55/kW)***

### Electrolyzer Stack Costs




***80% reduction since 2002***

## DOE Demonstrations

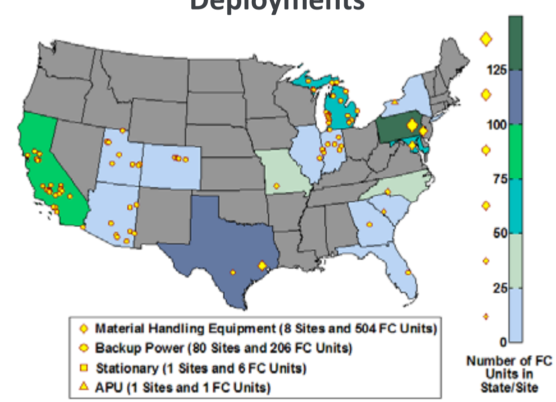

**Demonstrated**

- *>180 FCEVs*
- *25 stations*
- *3.6 million miles traveled*
- *World's first tri-gen station* (250 kW on biogas, 100 kg/d H2 produced)

## Deployments

- *DOE Recovery Act*
- *Market Transformation Projects*
- *Government Early Adoption (DoD, FAA, California, etc.)*
- *Tax Credits: 1603, 48C*

**Recovery Act & Market Transformation Deployments**

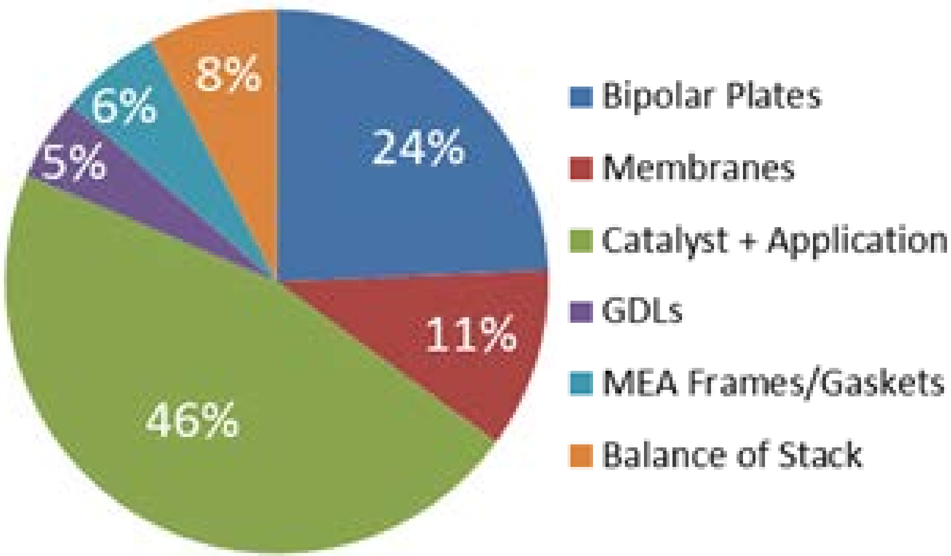



***~1,600 fuel cells deployed***
***>11,000 follow on orders***

# Fuel Cell Stack and PEM Electrolyzer System Cost Components

## Power electronics and stacks are large cost components of the PEM electrolyzer system while catalyst is a key challenge for fuel cell stack cost.

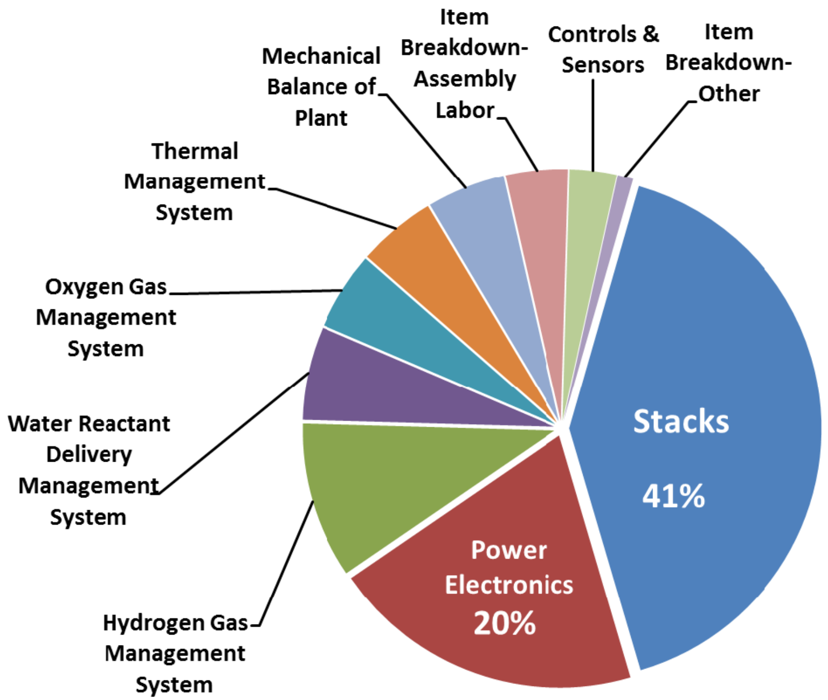
### Fuel Cell Stack Cost* Cost Breakdown




**Catalyst** accounts for **>45%** of total system cost

*For PEMFC Stack cost, 500,000 units per yr.
Cost is shows as $/kW-net.

### 2013 PEM Electrolyzer System Capital Cost




**Power Electronics, $H_2$ management** and **the stacks** accounts for **~70%** of PEM electrolyzer total system cost.

# WBG Revolution in Power Electronics

## Anant Agarwal, EERE/DOE


U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

# *What are Wide Band Gap (WBG) Semiconductors?*

| Si | SiC | GaN |
|---|---|---|
| 1.1 eV | 3.25 eV | 3.4 eV |
| In-direct band gap | In-direct | direct => LED |
| Max. Temp. = 125° C | 200° C | 250° C |
| Breakdown Field = 0.3 MV/cm | 2.2 MV/cm | 2.6 MV/cm |
| 6.5 kV IGBT | 15 kV MOSFET | 20 kV JFET |
| Electrons & holes => Slow Switching | Electrons Only => Fast Switching | Electrons Only => Fast Switching |
| 400 Hz | 4 kHz | 6 kHz |

Higher Temperature
Higher Voltage
Higher Frequency

→

More Efficient
Smaller, Cheaper
Power Electronics

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

# *SiC vs. GaN: Both technologies are critical to Power Electronics - in different voltage ranges*

- GaN based Power Electronics:
  - Suitable from 200 to 900 V
  - Ideal applications:
    - **0.1 to 10 kW Power Supplies**
    - **Laptop power adapters**
    - **Micro and string solar inverters up to 10 kW**
- SiC based Power Electronics:
  - Suitable from 900 to 15,000 V
  - Ideal applications:
    - **String solar inverters >10 kW**
    - **Central Solar and Fuel Cell Inverters up to several MW**
    - **Automotive Inverters and Quick Chargers**
    - **Traction**
    - **Medium Voltage Motor Control for Oil and NG high rpm direct drive**
    - **Distribution Grid Based Power Flow Controllers**

# Next Generation Power Electronics (WBG) Initiative Strategy

Power America Institute at NC State University

Capture U.S. opportunity for manufacturing leadership in:
Wide Bandgap Power Devices, Power Electronics

Commercial Foundry

Advanced Modules

Power Electronics

**Train Graduate Students in using WBG Devices in Power Electronics**

# Opportunities for SiC Power Electronics for Hydrogen and Fuel Cell Applications

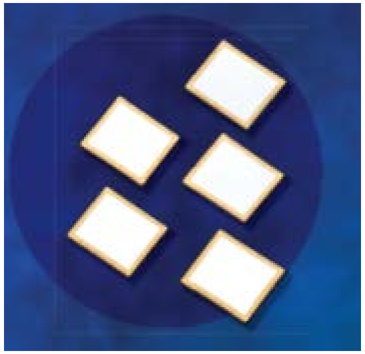
**Cree Power – Oct 2014**

**Jeff Casady, John Palmour, +001.919.308.2280 or jeffrey_casady@cree.com**

CREE

www.cree.com

# Cree SiC Portfolio - > 90 products from 2002-14



**DIODES SINCE 2002**
**>70 products and growing**

| | |
|---|---|
| 0650V | 2A-50A |
| 1200V | 2A-50A |
| 1700V | 50A |

die


TO-247

**MOSFETS SINCE 2011**
**>13 products and growing**

| | |
|---|---|
| 1200V | 7A-60A |
| 1700V | 3A-50A |


½ bridge


6-pack

**Power Modules SINCE 2012**
**>7 products and growing**

| | |
|---|---|
| 1200V | 20A-300A |
| 1700V | 250A |

# Cree 1700V, 8mΩ, ½ bridge power module released

Full commercial release – September 2014

Gate drivers, app notes available

First all-SiC power module released commercially @ 1700V

Available globally – Digikey, Mouser, Richardson/Arrow (right), …



2 channel; 1.2/1.7 kV 62 mm module gate driver direct mount

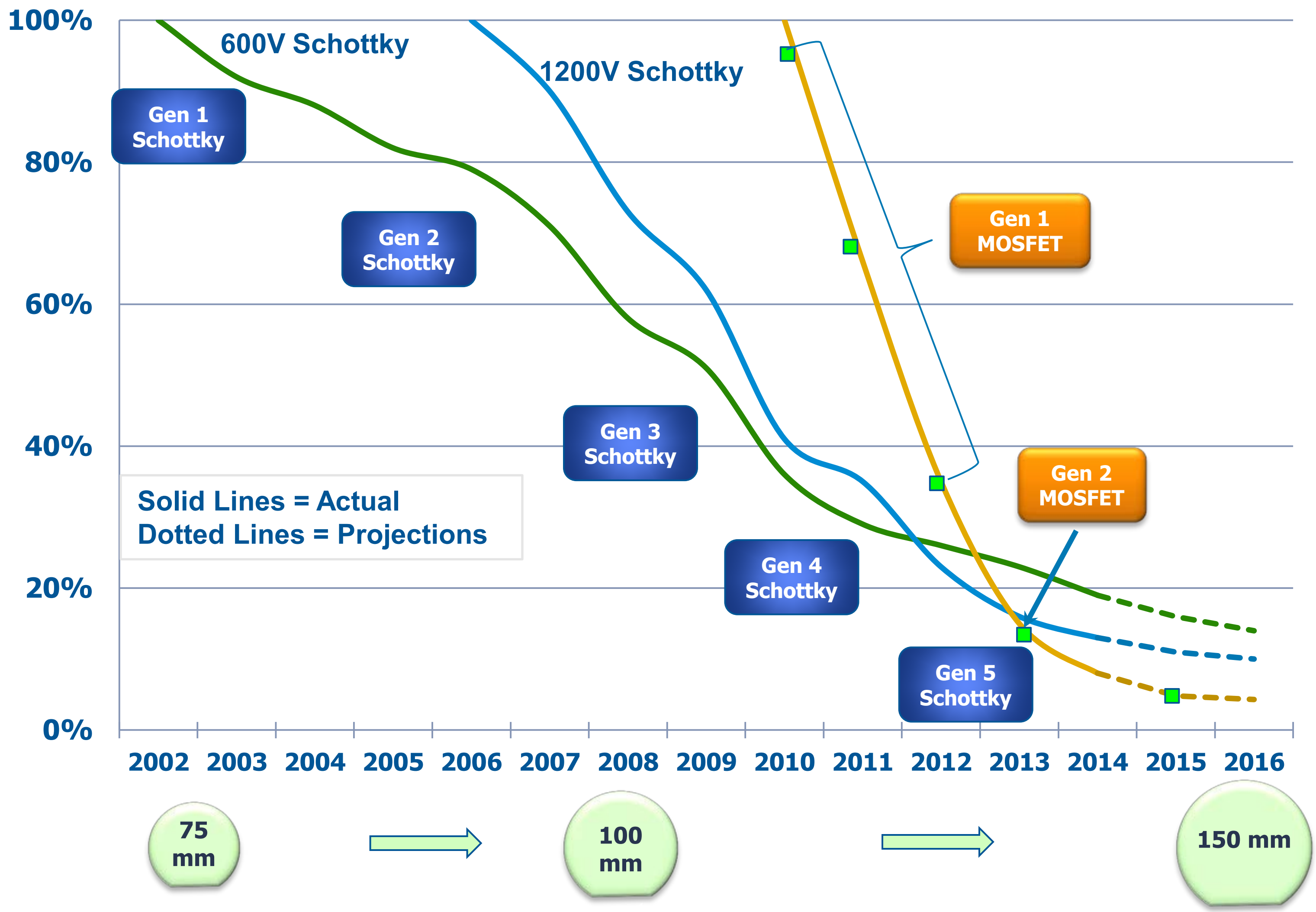
# Proven Reliability with Industry-Leading Standards

## Cree Field Failure Rate Data since Jan. 2004 through Oct. 2014

| Product | Device Hours | FIT (fails/billion hrs) |
|---|---|---|
| CSDxxx60 | 483,000,000,000 | 0.05 |
| C2Dxx120 | 171,000,000,000 | 0.43 |
| C3Dxxx60 | 481,000,000,000 | 0.02 |
| C4Dxxx120 | 46,800,000,000 | 0.04 |
| SiC MOSFET | 1,340,000,000 | 3.0 |
| Total | 1,183 Billion | 0.099 |

- **0.08 FIT rate is >10X lower than the typical silicon**
- **SiC diodes first released in 2001**
- **SiC MOSFETs first released in 2011**

# Cost reduction from volume and device refinement



Section – *Partial Listing* of

# Existing MOSFET Portfolio Applications

# 1200V SiC MOSFET design wins in PV inverters

"Through this partnership with Cree and their SiC technology, Sanix is able to capture more market share in the competitive Japan solar market," says Sanix's general manager Hiroshi Soga. "Cree's ... SiC switches reduced losses in our inverter electronics by more than 30% versus the silicon super-junction MOSFETs we were considering…"

PV Inverters
- lower losses, costs
- better performance


*April 2013 press release*

1200V, 80mΩ SiC MOSFETs have been selected by Japan's Sanix Inc.

9.9kW three-phase solar inverters

Higher power density, lower losses

*Sept 2014 press release*

# 1200V SiC MOSFET design win in induction heating

EFD INDUCTION

“The drop-in feature of Cree’s new all-SiC power module allows us to achieve 99 percent efficiency while reducing the power module count by a factor of 2.5 in our existing HF induction heating systems,” said John K. Langelid, R&D manager, EFD Induction. “These benefits are greatly valued as a reduced cost of ownership by our end customers.”

Induction Heating power supplies

- 2.5X lower part count
  - better implied reliability
- Reduction in power losses
- Reduced COO


*May 2014 press release*

# 1200 V SiC MOSFET win in on-board DC/DC converter

For HEV/EV bus (Shinry)

***Silicon***

***SiC***

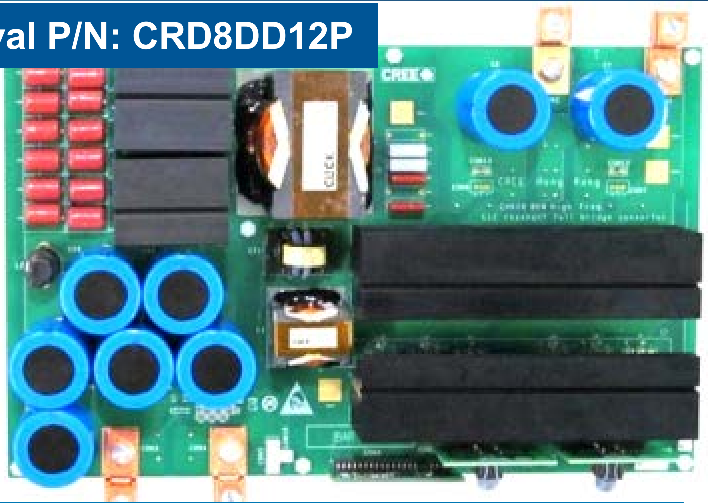
- DC-DC topology with 1200 V SiC MOSFET (***C2M0080120D***)
- Active clamp forward topology with 750 V DC in / 27 V DC out
- SiC MOSFET enabled:
    - ↑ **efficiency** from 88% to 96%
    - ↓ **size** and **weight** by 25% - 60%
    - ↓ both ***cost*** and audible noise
    - **Eliminated cooling fans**

# 1200 V SiC MOSFETs used in 8 kW EV charger demo

1200 V SiC MOSFET (C2M0160120D) enables:

- **Simpler topology, ½ the components,**
- **260 kHz, (> 35W/in³),**
- **Lower system cost, > 98.1% efficient**
- *Not possible to do this in silicon*

Cree eval P/N: CRD8DD12P

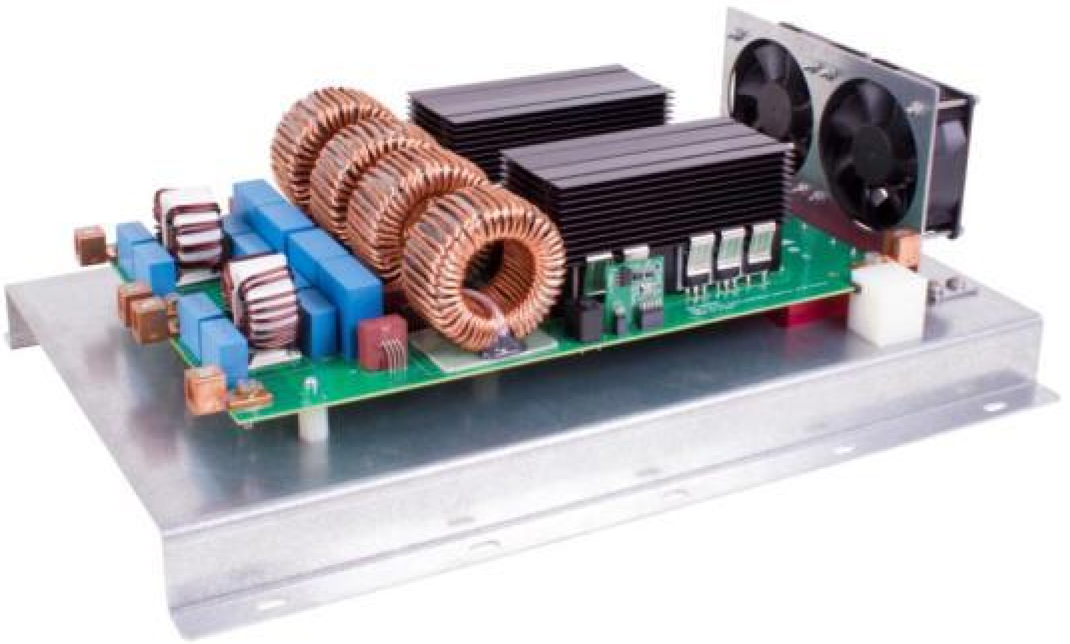


| Items | **3-level** FB w/ **Si** MOS @ **120kHZ** resonant freq. | **2-level** FB w/ **SiC** MOS @ **260kHZ** resonant freq. |
|---|---|---|
| MOSFETs<br>→ **650 V Si SPW47N60CFD in 3 level**<br>→ **1200 V SiC C2M0160120D in 2 level** | 16 pcs | 8 pcs |
| Flying diode | 4 pcs | None |
| Resonant Inductor (PQ3535) | 2 pcs | 1 pc Lr=15uH |
| Magnetize transformer | 2 pcs PQ5050 | 1 pcs PQ6560 Lm=100 uH |
| Resonant Capacitors | 35nF | 25 nF |
| MOS Drivers | 8 pcs | 4 pcs |
| Peak efficiency | 97.8% | 98.1% |

*Reference: J. Liu, "Highly efficient and compact ZVS resonant full bridge converter using 1200V SiC Mosfets," PCIM 2014*

# 1200V SiC MOSFET impact to 10-50 kW boost

- Benefits of SiC in power electronics are compelling in 10 to 50 kW boost stage
  - BOM cost decreases
  - Size, weight & losses all decrease
  - C2M0080120D compared to H3 IGBT*



| | Size | Weight | BOM | Losses | Temperature |
|---|---|---|---|---|---|
| 10 kW | 50% ↓ | 40% ↓ | 10-20% ↓ | 20% ↓ | 30% ↓ |
| 50 kW | 50% ↓ | 60% ↓ | 10-18% ↓ | 40% ↓ | 40% ↓ |

* *Reference: J. Liu (PCIM 2013)*

# Commercial PV installation 100kW – 1 MW

- Decentralized commercial roof top application.
- There is a need for a compact, **light weight, high power density**, three phase PV string inverter.
- Can lower installation cost and more widespread adoption of solar energy.
- SiC devices enable the best solution to achieve this need.

**Power density needed > 1 kW/Kg**

# What Is Used Today

| Kaco Blueplanet 50.0 TL3 | |
|---|---|
| **Full Power MPPT Voltage Range** | 480 – 850 VDC |
| **Operating MPPT Voltage Range** | 200 – 850 VDC |
| **No. Independent MPPT Input** | 1 |
| **Nominal output power** | 50 kW |
| **CEC Efficiency** | **97.5%** |
| **Peak Efficiency** | N/A |
| **Power Factor** | > 0.99 |
| **Output Voltage** | 480 Vac |
| **Operating Temperature Range** | -30 °C to 60 °C (**de-rated > 45 °C**) |
| **Cooling** | Forced convection |
| **Weight** | **173 kg** |
| **Isolation Transformer** | No |
| **Volume** | 840 × 355 × 1360 mm |

**50 kW, TL3 series**


**Power density = 0.29 kW/Kg**

**Need: Increase this value > 3 ×**

**Cree SiC Technology can achieve this…**

# What Can Be Done With Cree SiC Technology

| Cree SiC based 3-ph, PV String Inverter comparison | | |
|---|---|---|
| **Full Power MPPT Voltage Range** | 480 – 850 VDC | 450 – 800 VDC |
| **Operating Voltage Range** | 200 – 850 VDC | 400 – 950 VDC |
| **No. Indep MPPT Input** | 1 | 2 |
| **Nominal output power** | 50 kW | 50 kW |
| **CEC Efficiency** | 97.5% | 97.8% |
| **Peak Efficiency** | 98.3% | 98.7% |
| **Power Factor** | > 0.99 | > 0.99 |
| **Output Voltage** | 480 Vac | 480 Vac |
| **Operating Temperature Range** | -30 °C to 60 °C (de-rated > 45 °C) | -30 °C to 60 °C (no de-rating) |
| **Cooling** | Forced air | Forced air |
| **Weight** | 173 kg | 50 kg |
| **Isolation Transformer** | No | No |
| **Volume (m³)** | 0.41<br>840 x 355 x 1360 mm | 0.21<br>1000 x 700 x 300 mm |

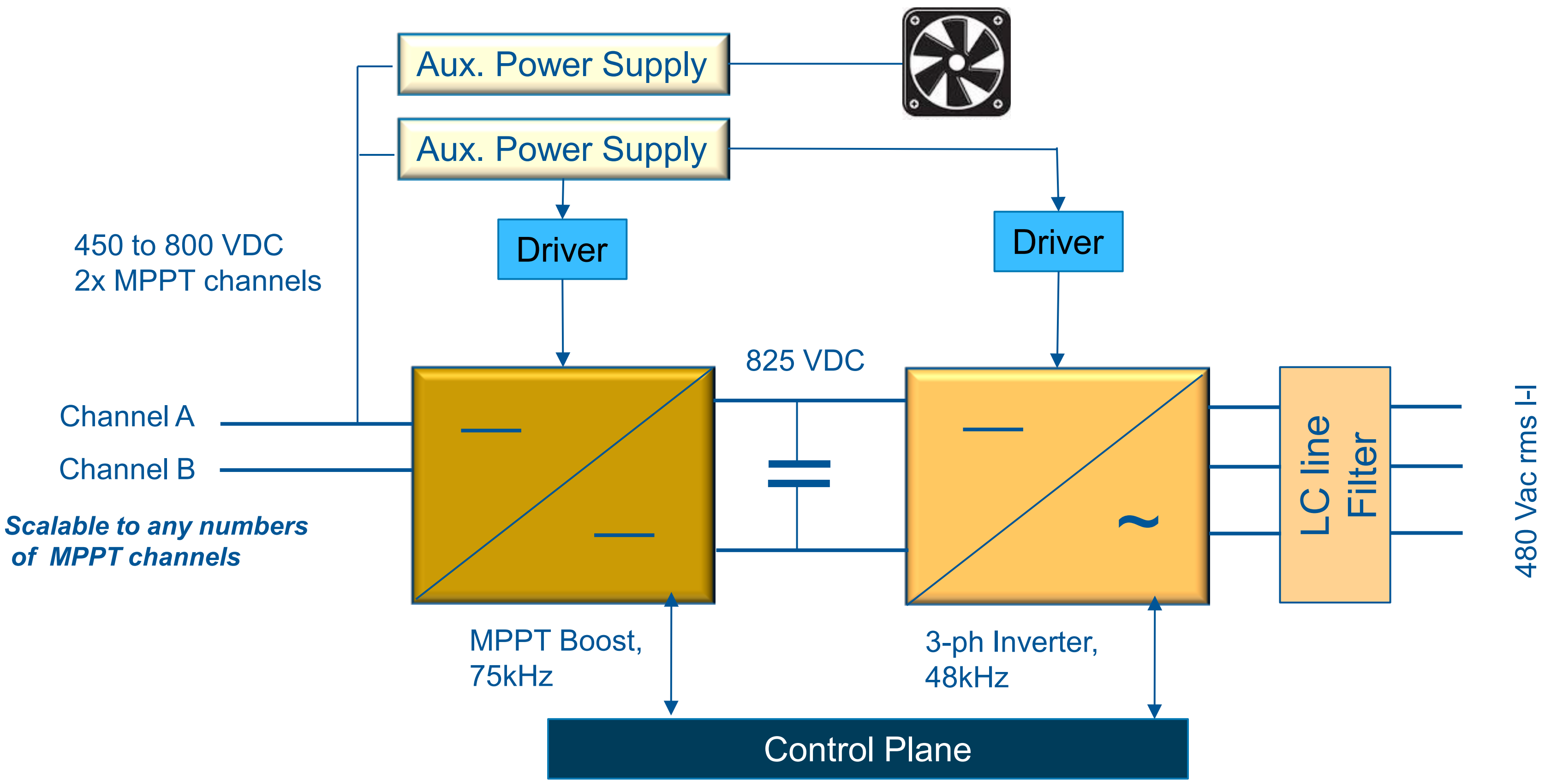


**SiC based 3-ph PV string Inverter**

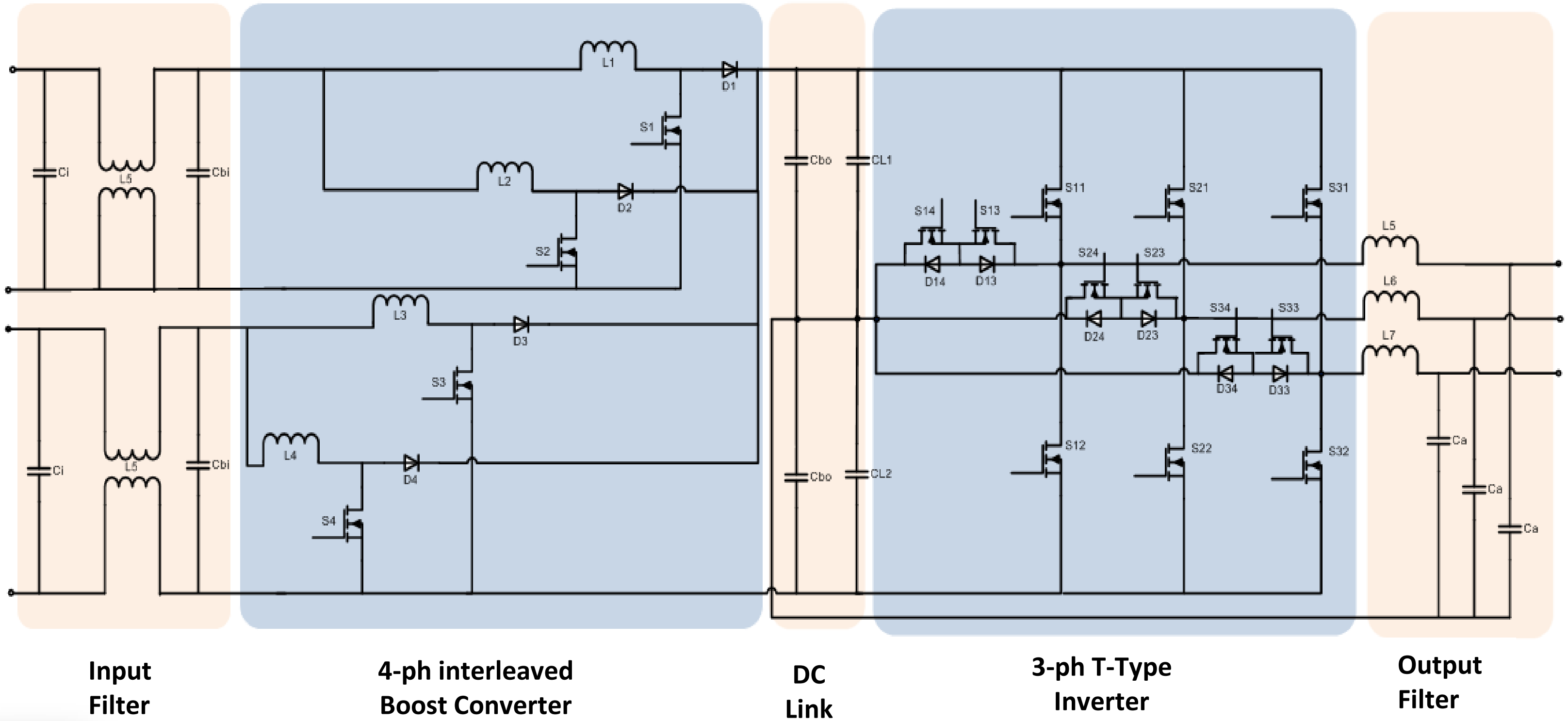
**Power Density = 1 kW/Kg**

# $50^{+}$kW PV Inverter Design

# SiC PV Inverter Reference design Overview



# PV String Inverter Schematic




2x C2M0080120D, SiC MOSFET in parallel per phase leg.

2x C4D10120D, SiC MPS diodes in parallel per phase leg.

10x 700uF 600VDC film

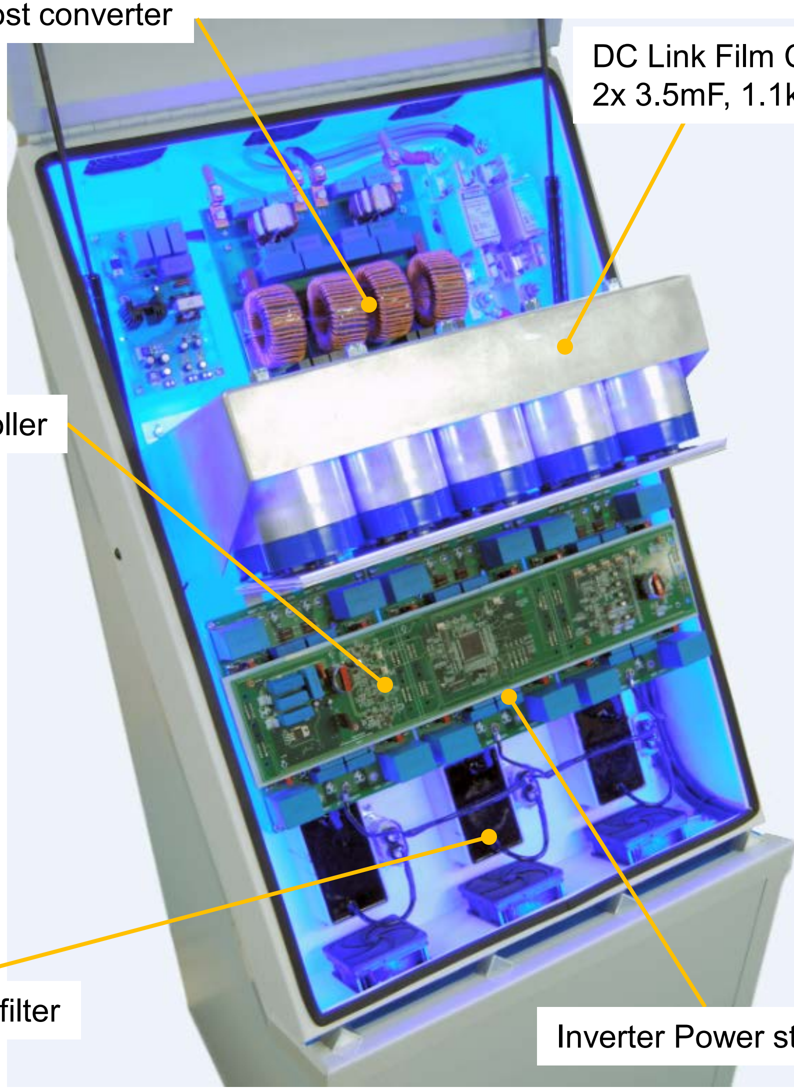
2x C2M0025120D, SiC MOSFET in parallel per phase leg upper and lower switch.

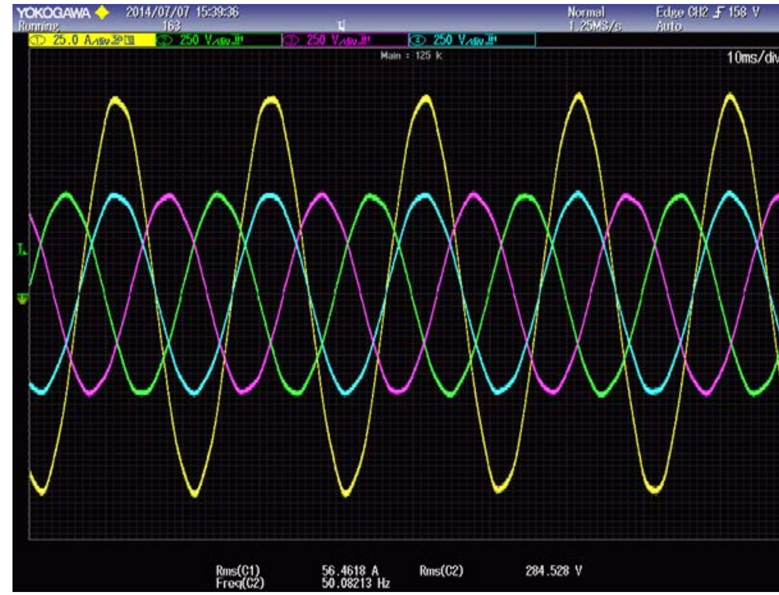
1x C2M0025120D, SiC MOSFET per T-leg.

1x C5D50065D, SiC MPS Diode per T-leg.

3x 4uF, 470Vac film
3x 230uH, metglas core

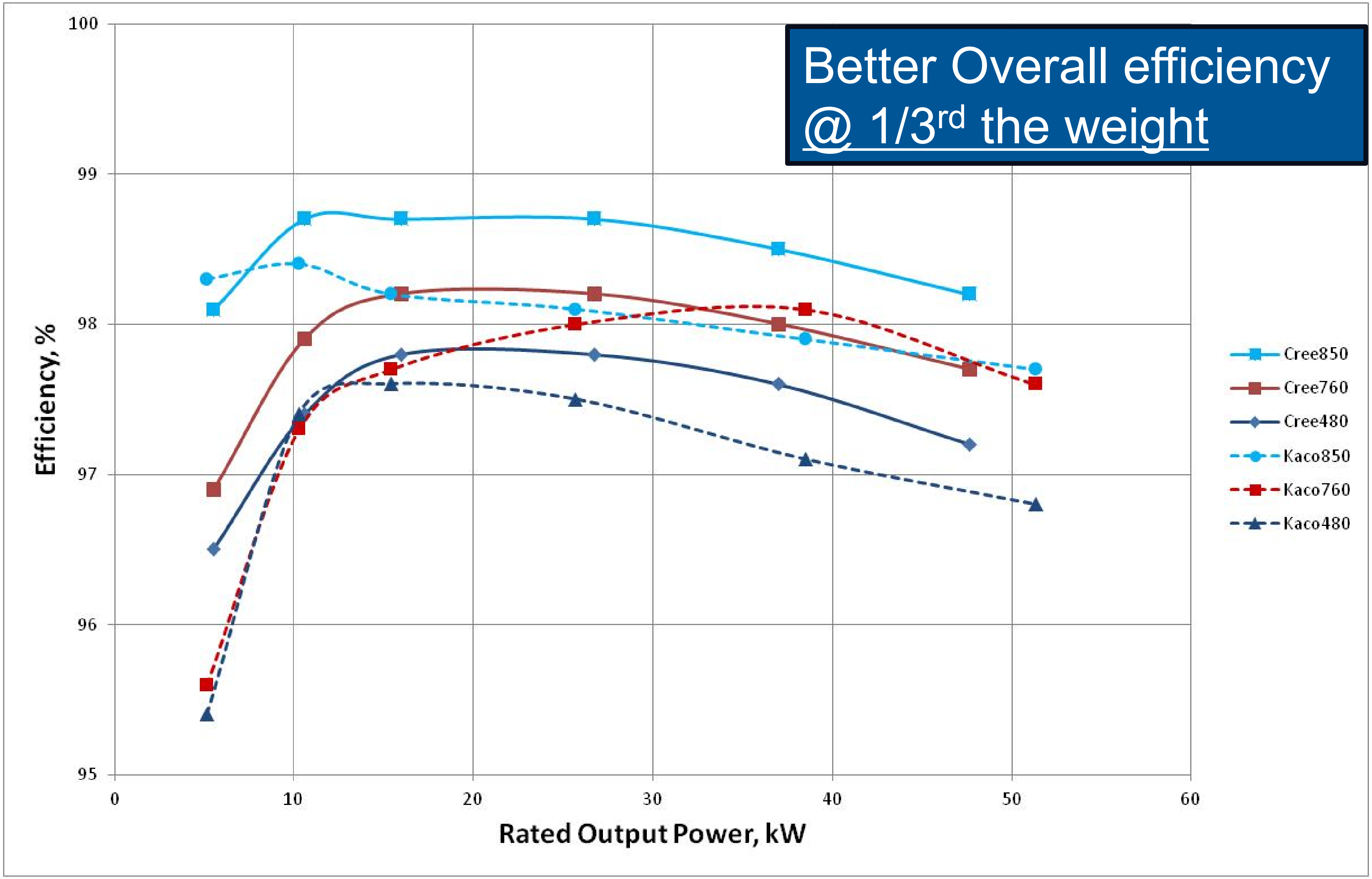
# All SiC 50kW PV String Inverter Test Assembly



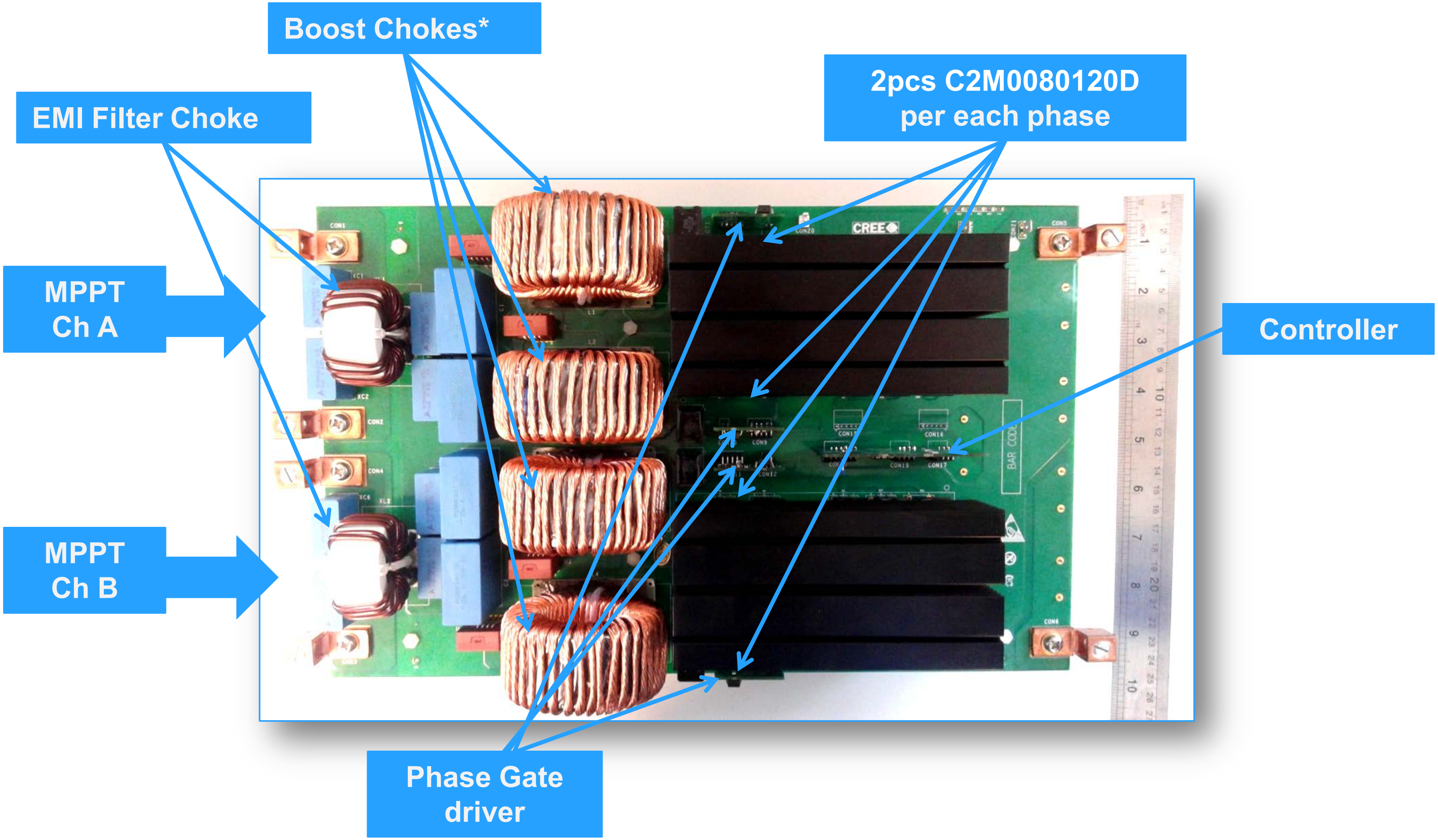

Output Power = 47.8kW
Output Voltage = 492 Vac l-l rms
Output Current = 56A rms
DC link Voltage = 850 VDC
3-phase, balanced resistive load

# SiC System Efficiency v/s Si based system*




* Independent test data for KACO BluePlanet 50.0 TL3 provided by gosolarcalifornia.ca.gov

# PCB Assembly Of The 50kW Evaluation Unit



# Electrical Specifications

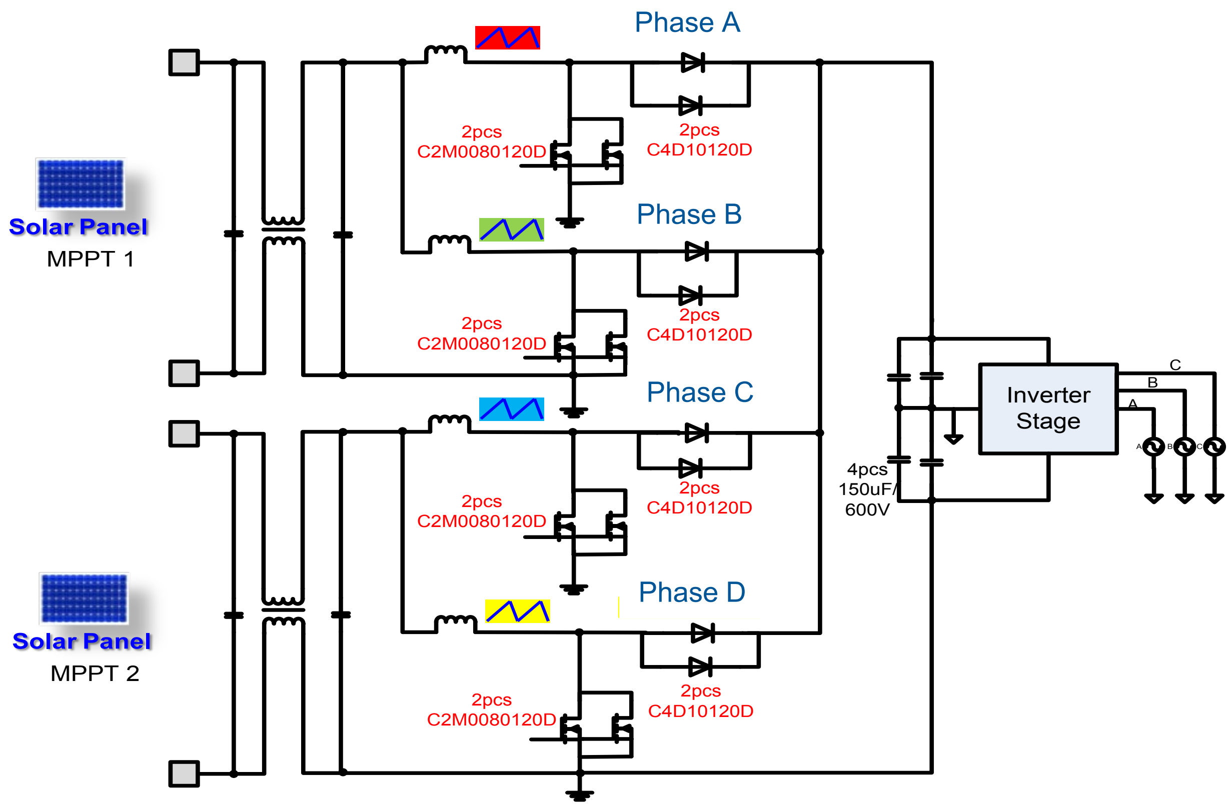
| Parameter | Unit | Value |
|---|---|---|
| DC output voltage | VDC | 800 |
| Max. output power | kW | 50 |
| DC input voltage | VDC | 400 – 600 |
| Efficiency | % | 97.8 – 99.14 |
| Switching Frequency / phase | kHz | 75 |
| Operating temp* | ºC | -25 to +35 |
| Storage temperature range | ºC | -35 to +85 |
| Isolation voltage | kV | tbd |

* Restriction imposed due to limited testing for evaluation products.

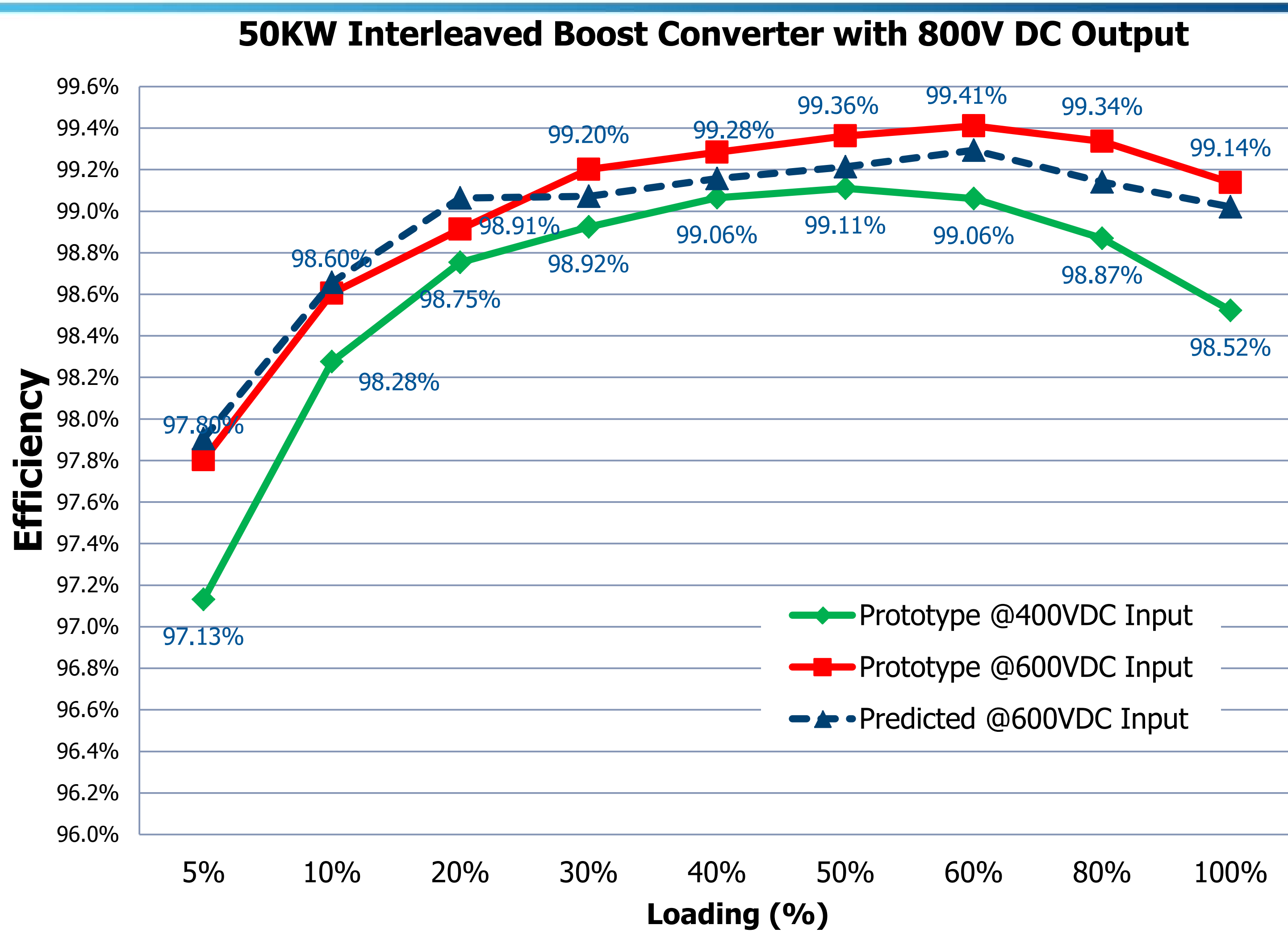
Hardware designed as an evaluation platform and not a qualified product.

# 50kW, 4 phase Interleaved Boost Converter Features

- ✓ 2x devices hard paralleled per phase
- ✓ 4 phase interleaved Boost with full SiC devices
- ✓ Input voltage: 400V-600Vdc
- ✓ Output voltage: 800Vdc
- ✓ Output power: 50KW (12.5KW per channel)
- ✓ Controller preset
- ✓ 2x independent MPPT channels



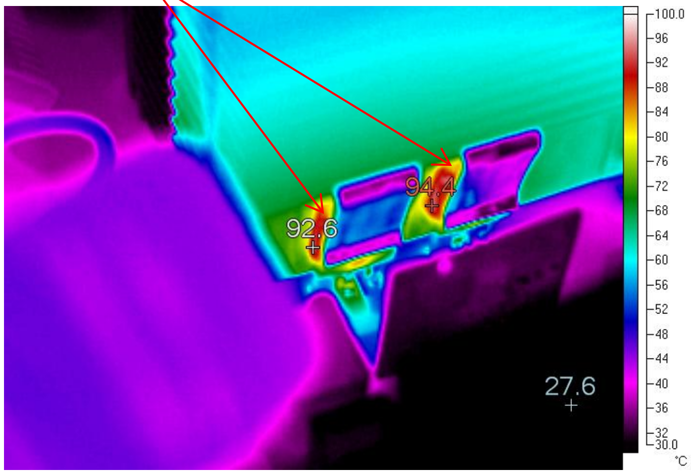
# Measured Versus Calculated Efficiency Over Varying Load



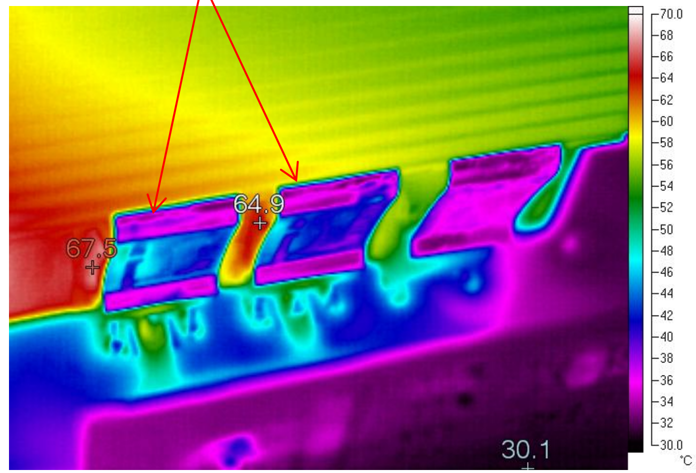

Note: Gate to source turn on resistor is 15Ohm and turn off resistor is 5Ohm
Ambient temperature is 25° C with fan cooling

# Thermal Images With 400V In / 800V Out at Full Load

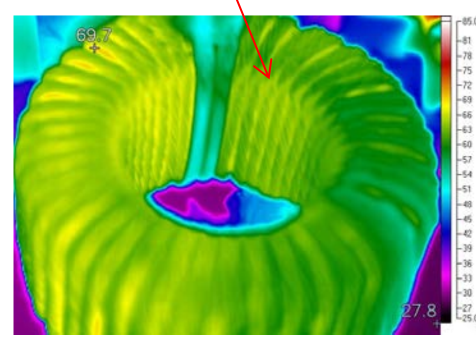
C2D0080120D




C4D10120D




Boost Inductor

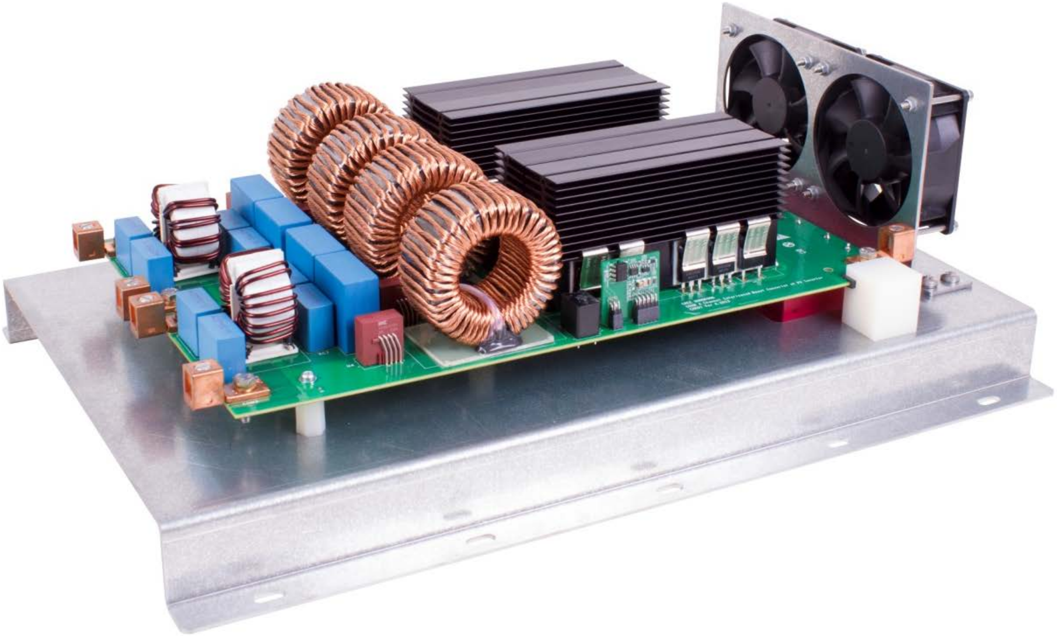



| Part | Tc (°C) #1 | Tc (°C) #2 |
|---|---|---|
| C2M0080120D | 92.6 | 94.4 |
| C4D10120D | 67.5 | 64.9 |
| Boost Inductor | 69.7 | |

Note: Testing is based on full load operation after 30min with fan to cool system
Ambient temperature = 25ºC

# 50kW Boost Evaluation unit Availability

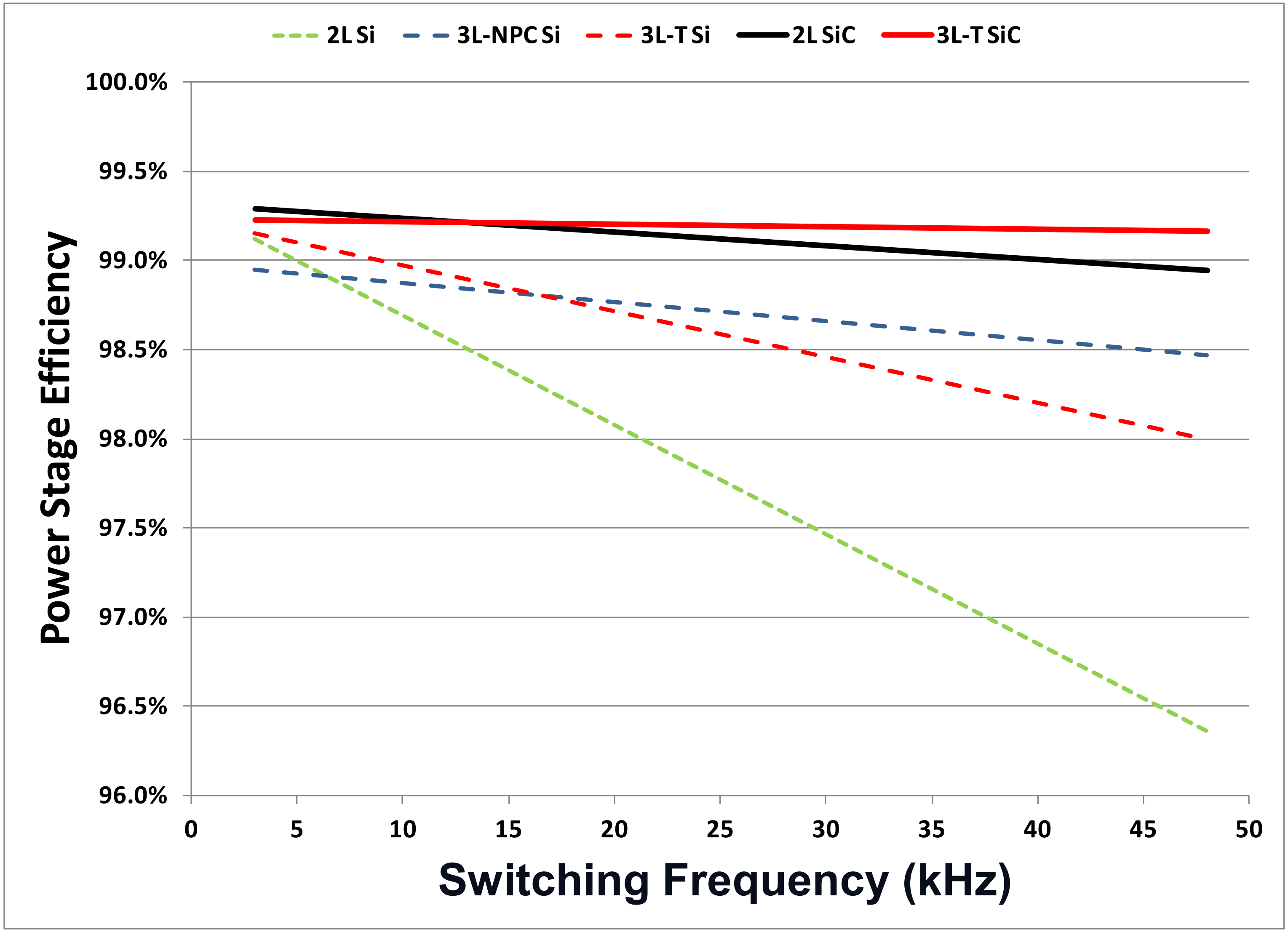
- Order P/N: **CRD50DD12N**
- Estimated cost per unit: $4,000 USD
- CAD model in STEP format available
- Available now
- Schematic and layout files available



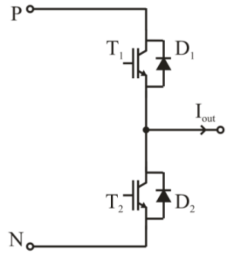
Hardware designed as an evaluation platform and not a qualified product.

# 3-Phase Inverter

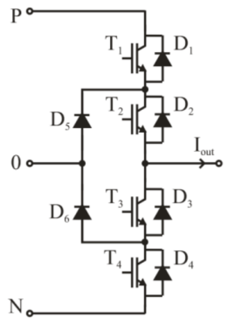
# Topology Analysis For 3-Phase Inverter



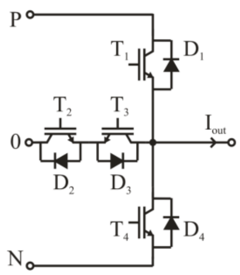

2L



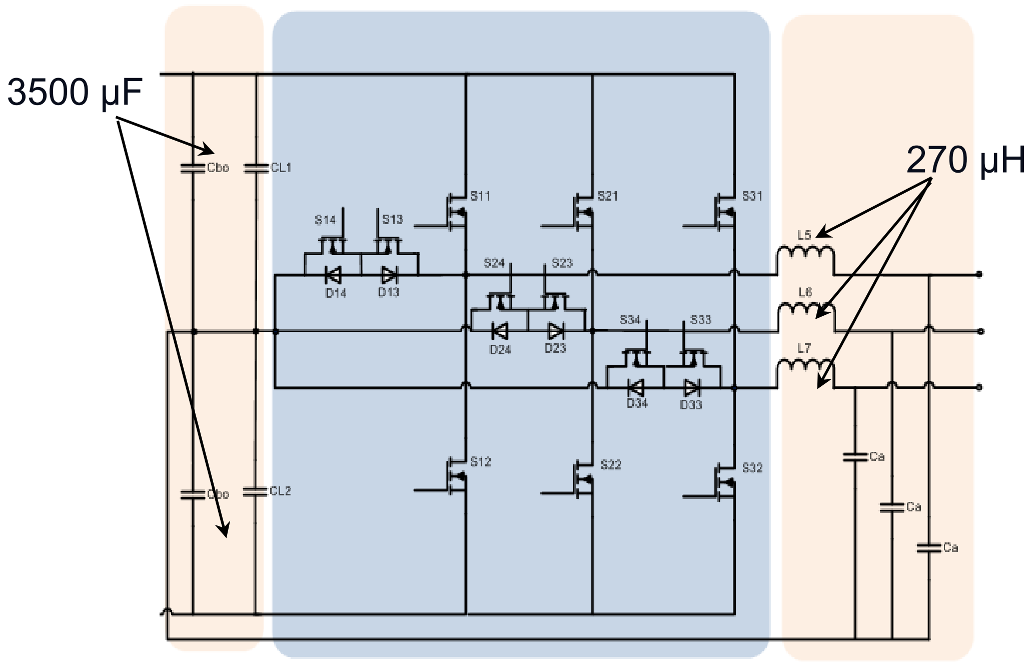
3L-NPC

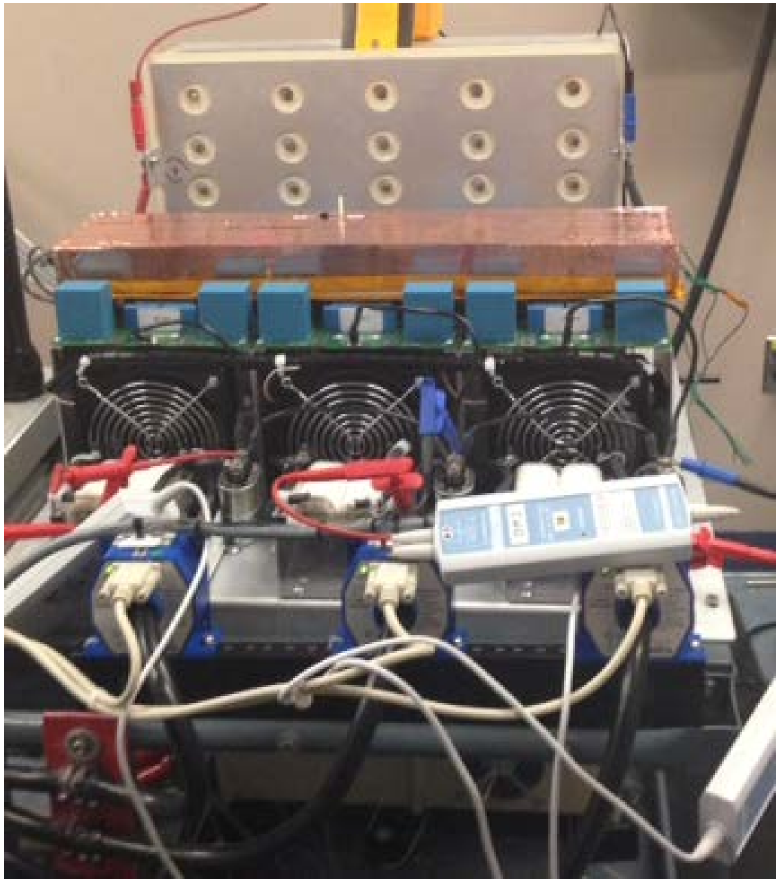


3L-T



# Inverter Topology – three level T-type



Main Lower & Upper MOSFET position: 2x Cree 1.2kV SiC Mosfet, 60A, 25 mΩ
Main Diode position: None, uses MOSFET Body diode
T-Branch MOSFET position: 1x Cree 1.2kV SiC Mosfet, 60A, 25 mΩ
T-branch Diode position: 2x Cree 650V, 50A, C3D50065D

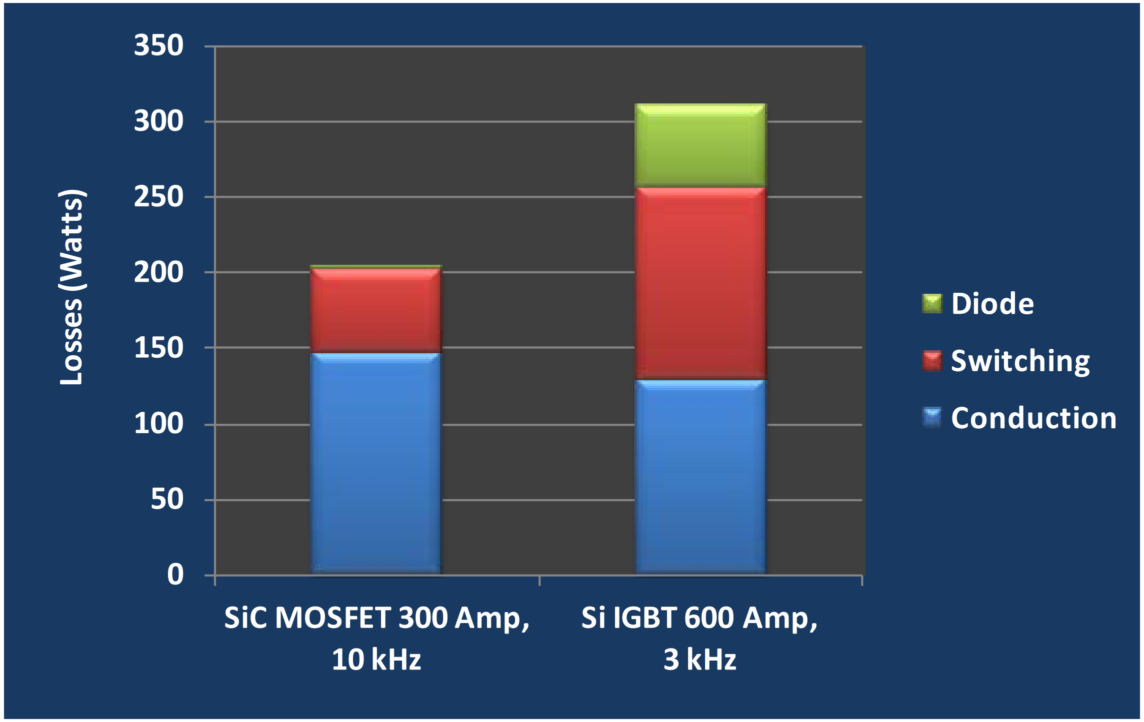
Section –

# Future SiC MOSFET products – scaling to medium voltage

# SiC amp ratings are much less than Si

**Si Amps are *not* SiC Amps**

**300 Amp SiC More Capable than 600 Amp Si IGBTs!**




- System cost reduction of 20% using 1200V SiC
  - Increased frequency reduces size and weight of magnetics
  - Lower losses reduce system cooling requirements
  - Amperage rating for SiC less than half required for Si IGBTs

# SiC voltage ratings are much less than Si?

**Si Volts are *not* SiC Volts**

**6.5 kV Si IGBT used for 3.6 kV drives (100 cosmic ray FIT rate)**

**4.5 kV SiC MOSFET used for 3.6 kV line?**

**10 kV SiC MOSFET used for 7.2 kV?**

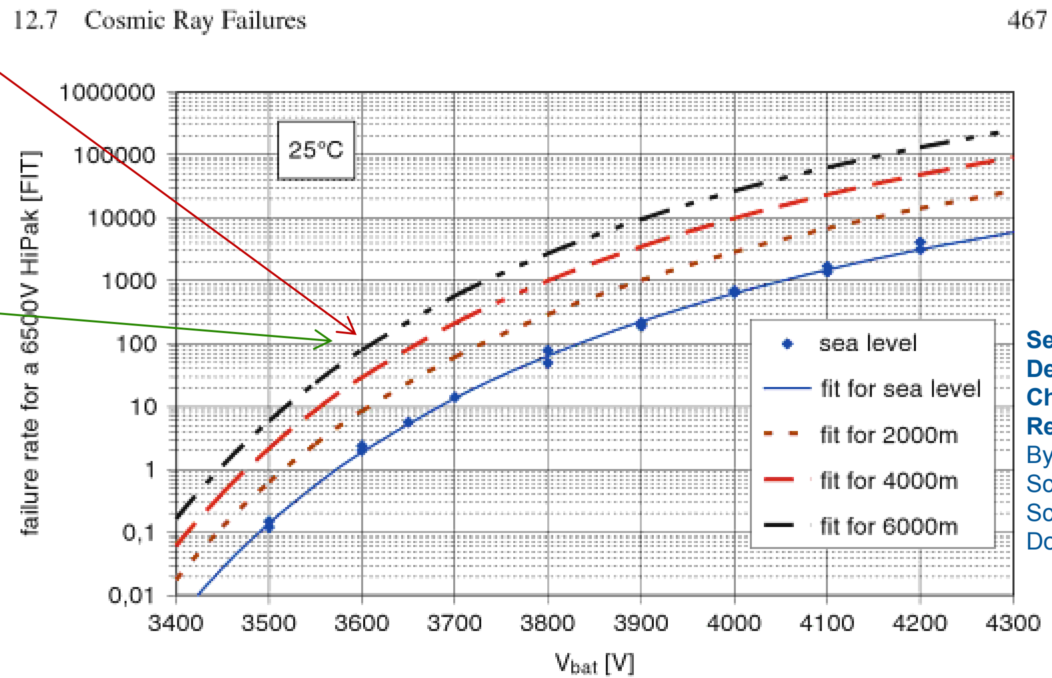



**Fig. 12.49** Cosmic ray failure rate at $T = 25°C$ for the 6.5 kV IGBT module 5SNA0600G650100 from ABB. Figure from [Kam04]

**Semiconductor Power Devices: Physics, Characteristics, Reliability**
By Josef Lutz, Heinrich Schlangenotto, Uwe Scheuermann, Rik De Doncker

- **Medium Voltage SiC MOSFET roadmap must respond to application**
  - **10X higher switching frequency, lower thermal dissipation possible**
  - **Cosmic ray, other reliability metrics may be 100X better**
  - **All requirements, eg. short circuit, surge must be understood**

Section –

# Future Target Applications

# Application Market Pull for MV SiC from:

- **AC Medium Voltage Drives Applications**
- **Railway Applications** **(3.3 kV SiC already being adopted in rail)**
- **Grid-tied Solar Applications**
- **HVDC Applications** **(Off-shore wind, hydro, …)**
- **Grid-tied Power Distribution** **(Energy-intensive structures such as factories, data centers)**

**Transport Electrification**

**Energy Distribution**

**Rail & Grid-tied Energy**

# 10 kV SiC MOSFETs in Boost Converter (Fraunhofer ISE)

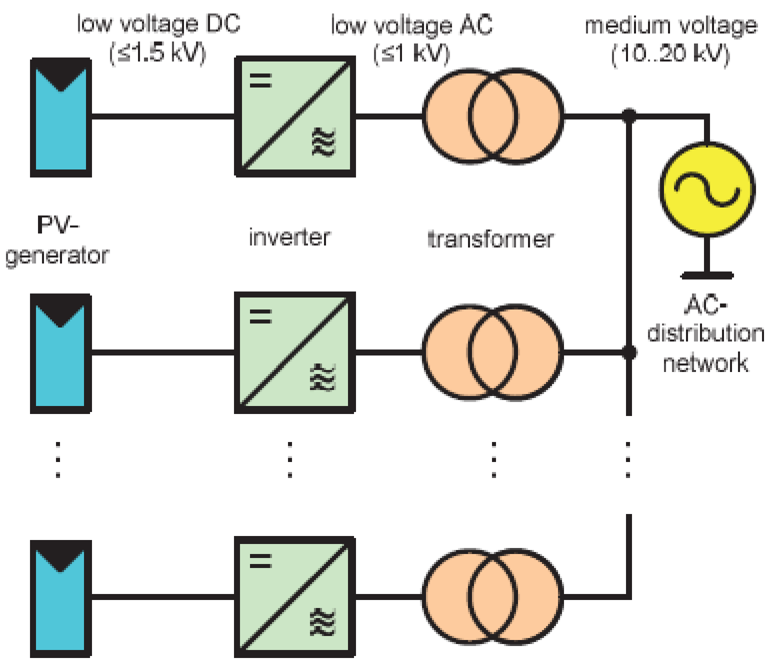



Fig. 1. Topology of today's PV power plants

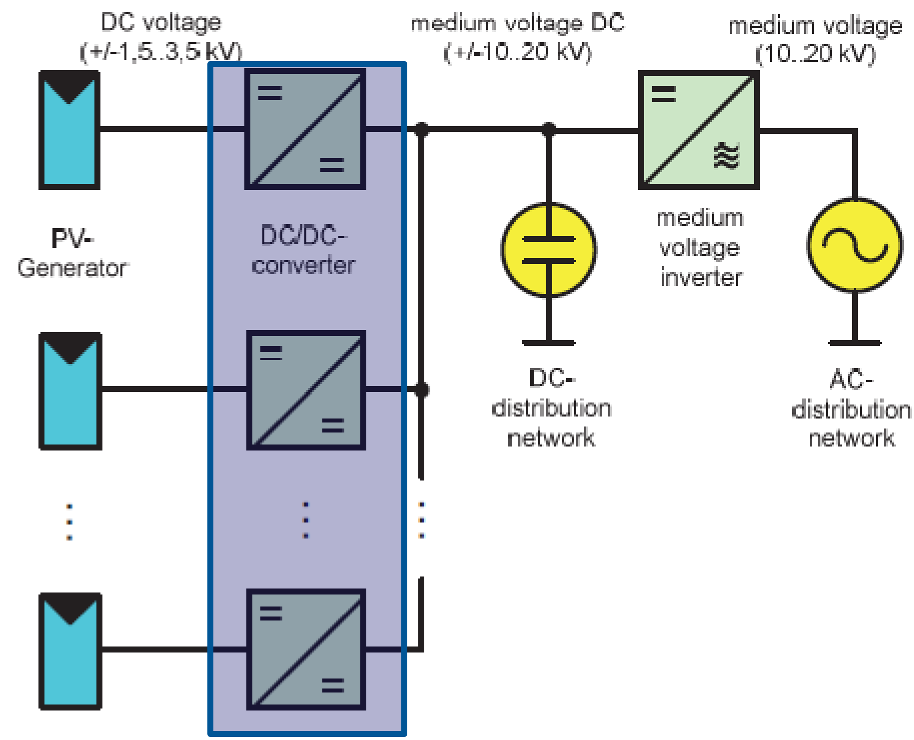



Fig. 2. Conceivable topology of future PV power plants

## Advantages of medium voltage DC distribution:

- Flexible subunit power rating from a few kW to > 2 MW
- Smaller, lighter, cheaper power cables with higher voltage
- Eliminate large, heavy, costly transformer
- Reduce number of system components

Fraunhofer ISE

*A Highly Efficient DC-DC-Converter for Medium-Voltage Applications*
*Jürgen Thoma, David Chilachava, Dirk Kranzer*
*ENERGYCON 2014 • May 13-16, 2014 • Dubrovnik, Croatia*

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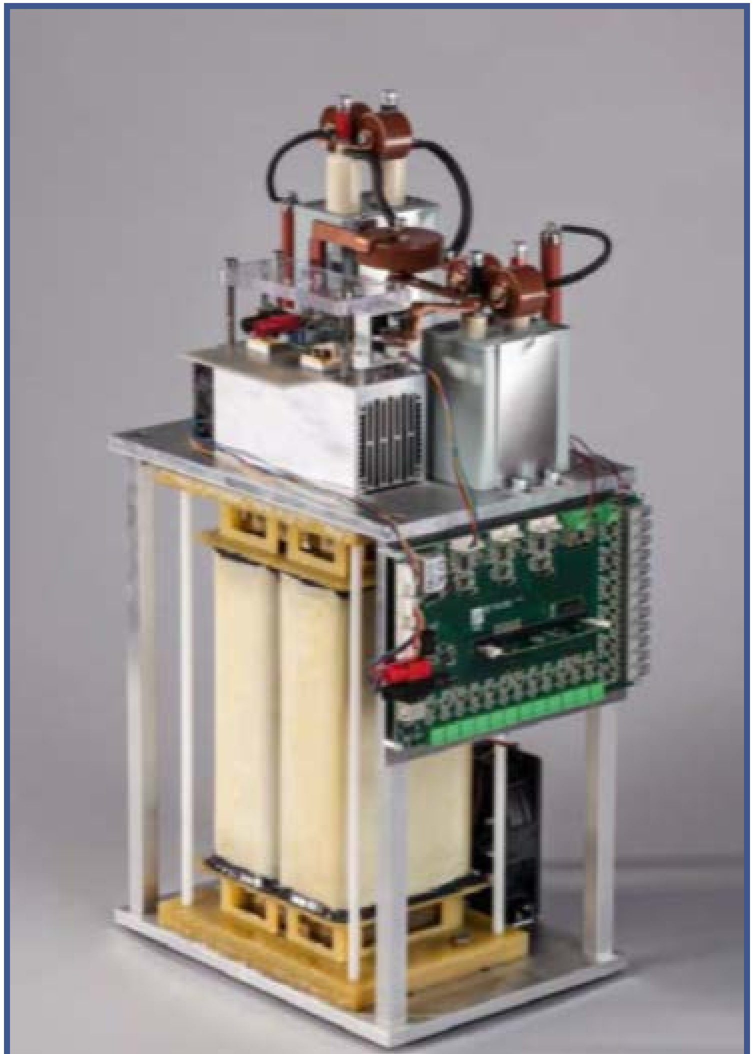

Box is 36 cm x 30 cm

Efficient, "transformer-less" power distribution to medium voltage grid

- **Fraunhofer DC-DC converter used 10kV SiC MOSFETs from Cree**
- **30 kW DC voltage converter with 3.5 kV input voltage, 8.5 kV output voltage, 98.5% efficient**
- **8kHz switching frequency 15X higher than possible with conventional silicon devices in the same voltage range.**

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# Thank You

amit.talapatra@ee.doe.gov

**Presenters:** Jeff Casady (Jeffrey_Casady@cree.com) and John Palmour (john_palmour@cree.com) of Cree Inc.

**DOE Hosts:** Eric Miller (eric.miller@ee.doe.gov) and Anant Agarwal (anant.agarwal@ee.doe.gov)