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

High-Voltage, High-Frequency Semiconductor Devices, Smart Grid Power Conditioning Systems, Metrology for HV-HF Device and u-Grid PCS

Allen Hefner

National Institute of Standards and Technology
Power Electronics Technologies, and Smart Grid

Grid Transformation via PCS Functionality

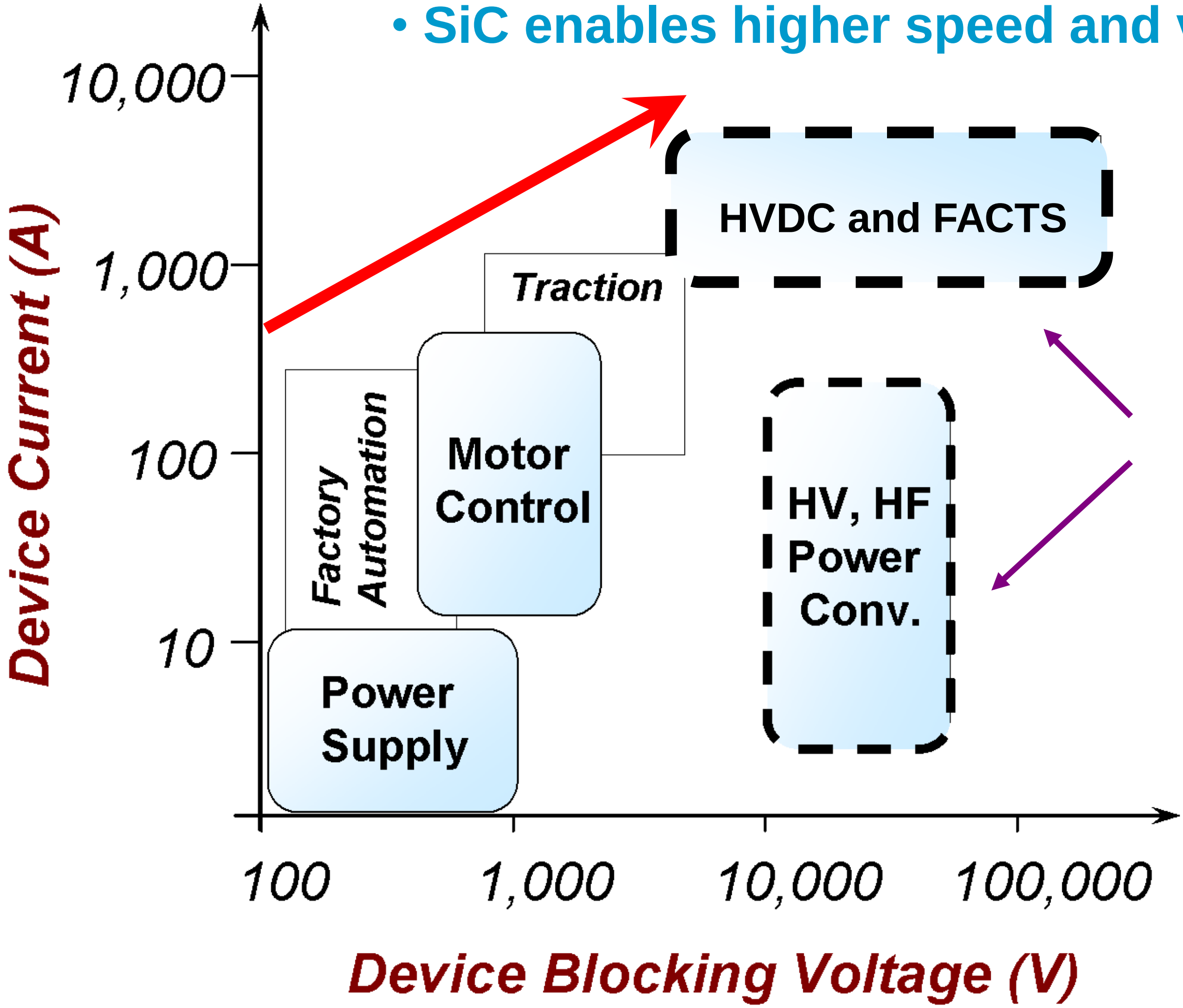
- **Today's Grid:**
  - Electricity is generated by rotating machines with large inertia
  - Not much storage: generation instantaneously matches load using
    - load shedding at large facilities
    - low efficiency fossil generators for frequency regulation
- **Future Smart Grid:**
  - High penetration of renewables with power electronic grid interface:
    - dispatchable voltage, frequency, and reactive power
    - response to abnormal conditions without cascading events
    - dispatchable "synthetic" inertia and spinning reserve (w/ storage)
  - Storage for frequency regulation and renewable variability / intermittency
    - High-speed and high-energy storage options
    - Load-based "virtual storage" through scheduling and deferral
  - Plug-in Vehicles increase efficiency, provide additional grid storage
  - HVDC, DC circuits, SST, SSCB provide stability, functionality and low cost
- **Microgrids & automation provide secure, resilient operation**

HV-HF Switch Mode Power Conversion

- **Switch-mode power conversion (Today):**
  - **advantages: efficiency, control, functionality, size, weight, cost**
  - **semiconductors from: 100 V, ~MHz to 6 kV, ~100 Hz**
- **New semiconductor devices extend application range:**
  - **1990's: Silicon IGBTs**
    - **higher power levels for motor control, traction, grid PCS**
  - **Emerging: SiC Schottky diodes and MOSFETs, & GaN**
    - **higher speed for power supplies and motor control**
  - **Future: HV-HF SiC: MOSFET, PiN diode, Schottky, and IGBT**
    - **enable 15-kV, 20-kHz switch-mode power conversion**

Power Semiconductor Applications

- Switching speed decreases with voltage
- SiC enables higher speed and voltage



Power distribution, transmission and generation

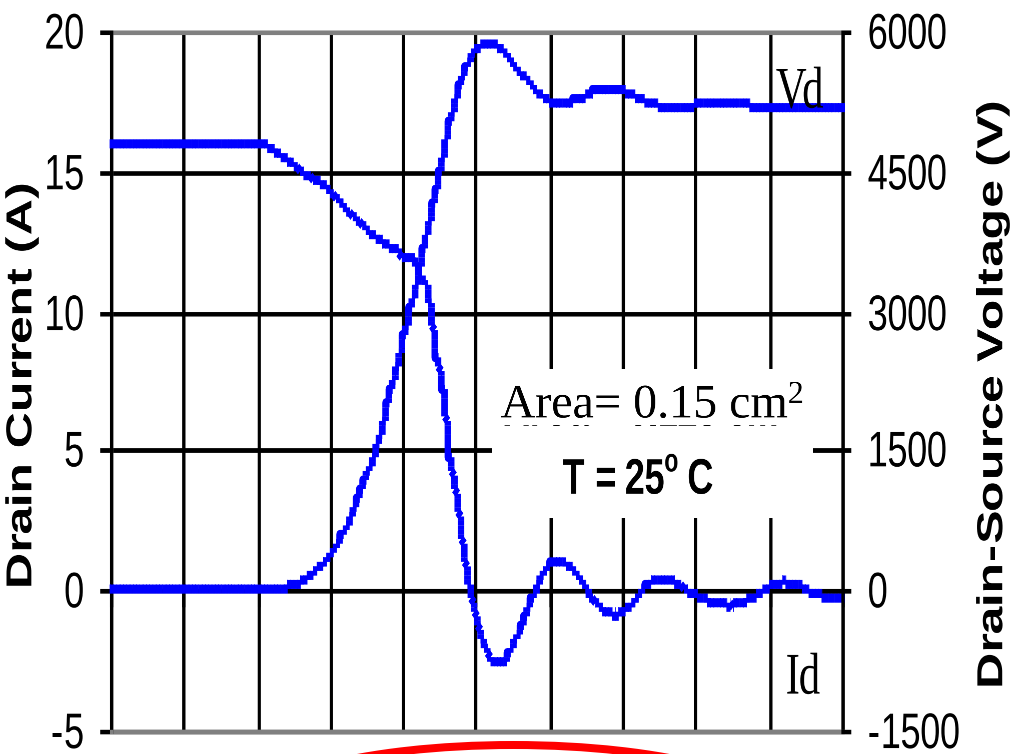
A. Hefner, et.al.; "SiC power diodes provide breakthrough performance for a wide range of applications" IEEE Transactions on Power Electronics, March 2001, Page(s):273 – 280.

DARPA/ONR/NAVSEA HPE Program

10 kV HV-HF MOSFET/JBS

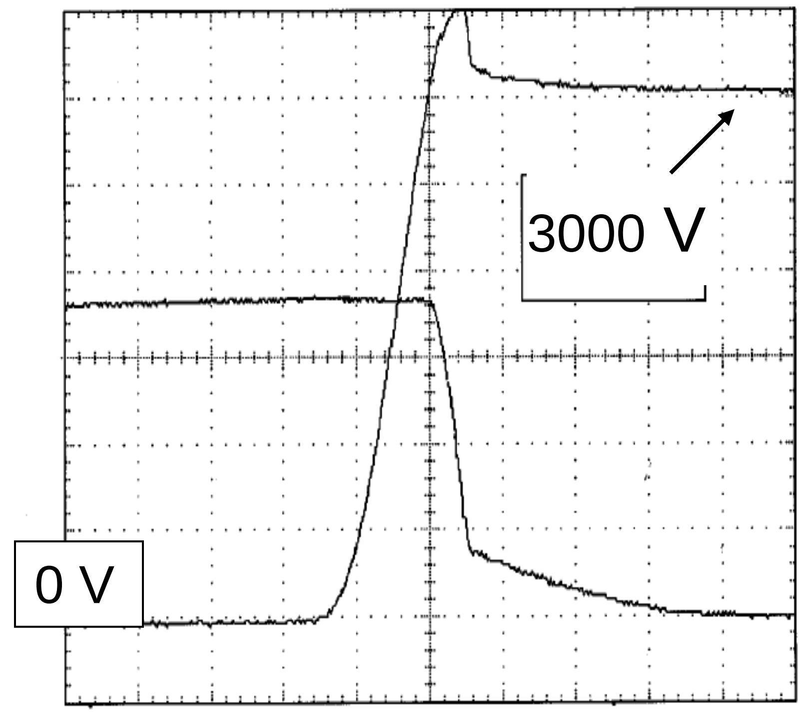
High Speed at High Voltage

SiC MOSFET: 10 kV, 30 ns



15 ns /div

Silicon IGBT: 4.5 kV, 2us

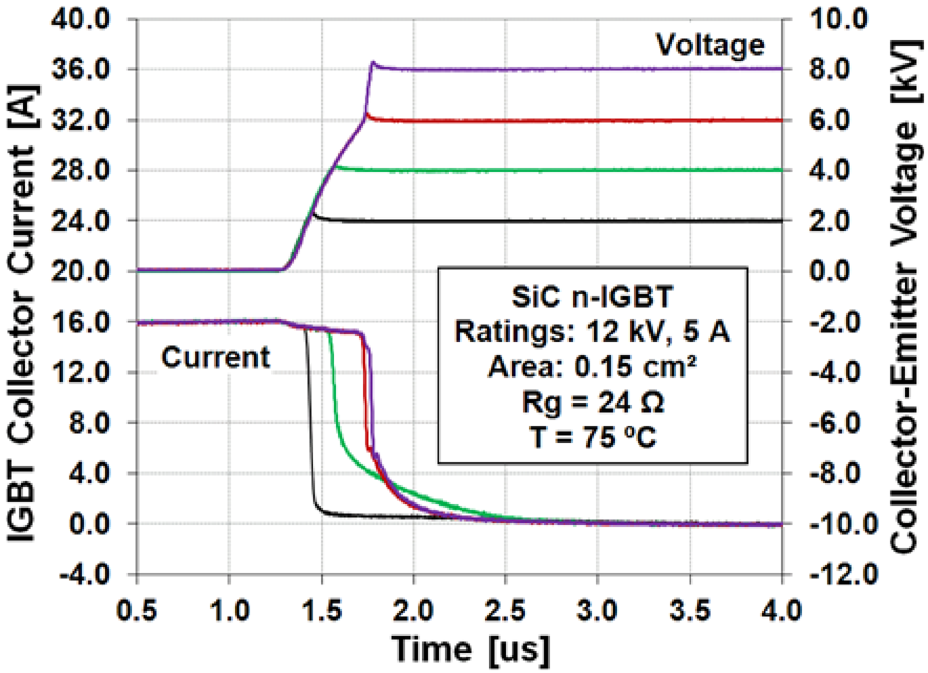


1us /div

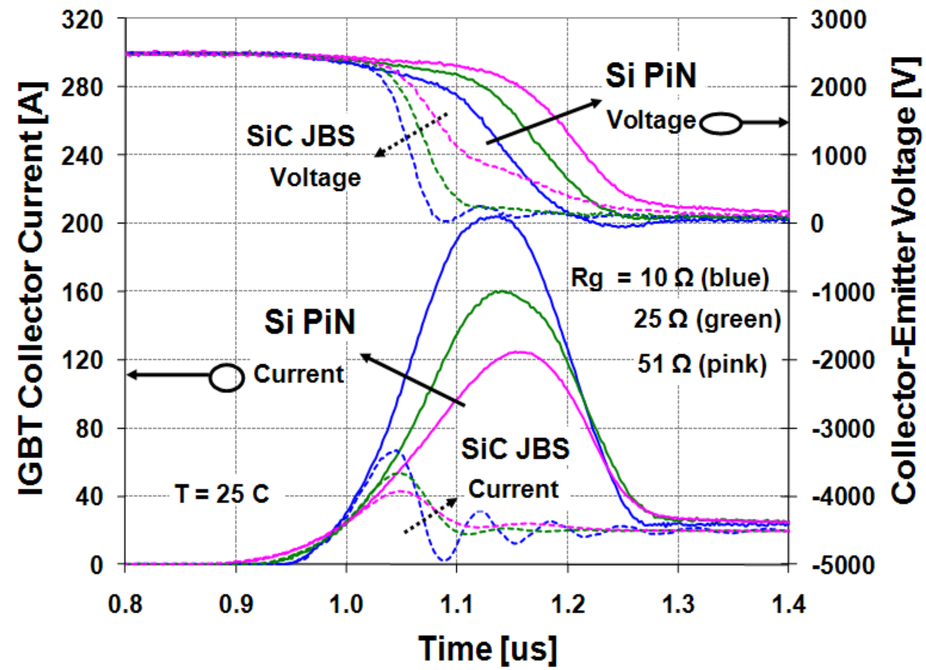
A. Hefner, et.al. “Recent Advances in High-Voltage, High-Frequency Silicon-Carbide Power Devices,” *IEEE IAS Annual Meeting,* October 2006, pp. 330-337.

ARPA-e ADEPT	NRL/ONR
12 kV SiC IGBT	**4.5 kV SIC-JBS/Si-IGBT**
Future option	**Low cost now**

SiC IGBT: HV, high Temp, 1 us



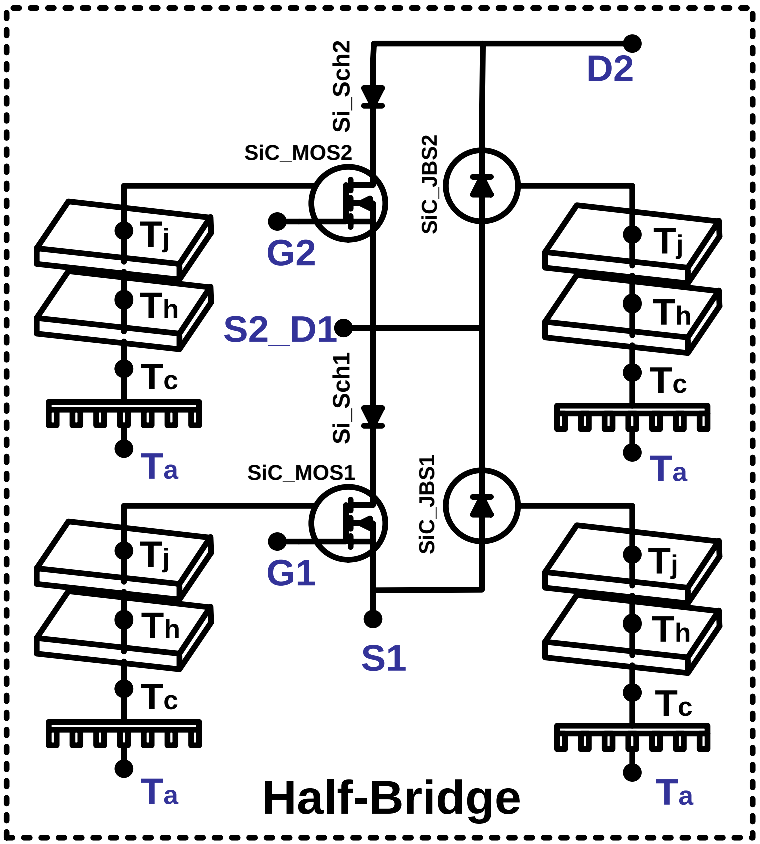
SiC JBS: improves Si IGBT turn-on



Sei-Hyung Ryu, Craig Capell, Allen Hefner, and Subhashish Bhattacharya, "High Performance, Ultra High Voltage 4H-SiC IGBTs" Proceedings of the IEEE Energy Conversion Congress and Exposition (ECCE) Conference 2012, Raleigh, NC, September 15 – 20, 2012.

K.D. Hobart, E.A. Imhoff, T. H. Duong, A.R. Hefner "Optimization of 4.5 kV Si IGBT/SiC Diode Hybrid Module" PRiME 2012 Meeting, Honolulu, HI, October 7 - 12, 2012.

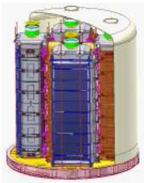
10 kV SiC MOSFET/JBS Half-Bridge Module Model and Circuit Simulation



- **Half-bridge module model:**
  - 10 kV SiC power MOSFETs
  - 10 kV SiC JBS for anti-parallel diodes
  - low-voltage Si Schottky diodes
  - voltage isolation and cooling stack
- **Validated models scaled to 100 A, 10 kV half bridge module**
- **Model used to perform simulations necessary to:**
  - optimize module parameters
  - determine gate drive requirements
  - SSPS system integration
  - high-megawatt converter cost analysis

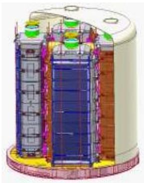
SECA: 300 MW PCS

~700 V DC



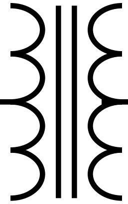
Approx. 500 Fuel Cells

~700 V DC



Semiconductors
Packaging and Interconnects
HF transformers
Filter Inductors and Capacitors
Cooling System
60 Hz Transformer up to 18 kV
Breakers and Switchgear

18 kV AC



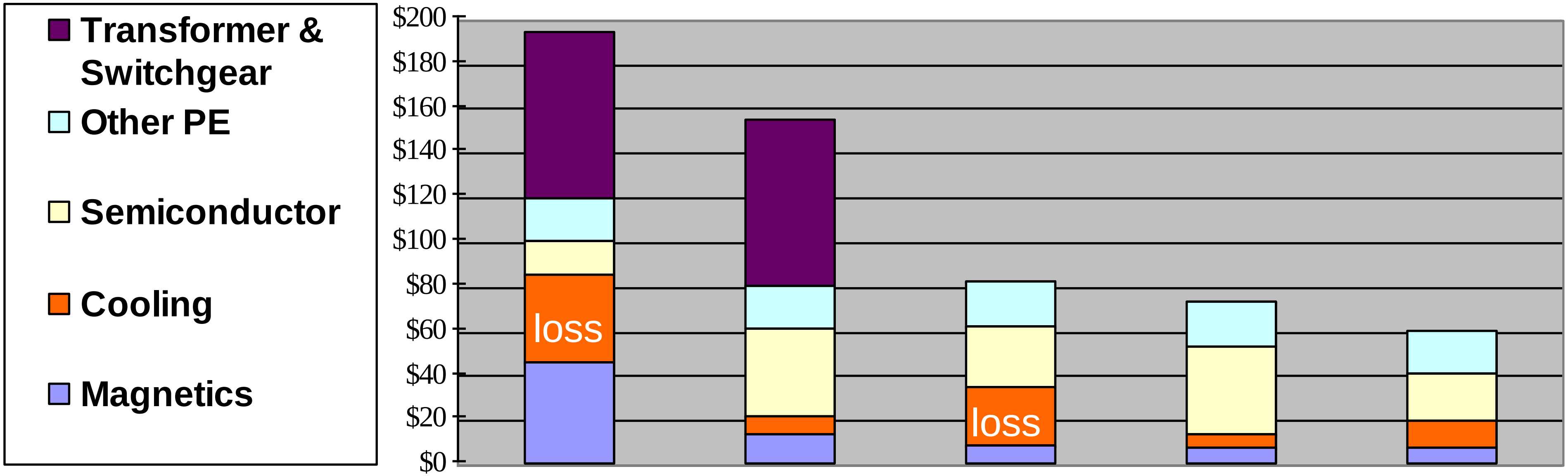
345 kV AC

$40-$100 / kW

Ripple < 2%
Stack Voltage Range
~700 to 1000 V

IEEE – 519
IEEE – 1547
Harmonic Distortion
Future: HVDC transmission ?

Estimated $/kW: MV & HV Inverter



Inverter Voltage	Medium	Medium	High	High	High
HV-SiC Diode		Schottky	Schottky	Schottky	PiN
HV-SiC Switch		MOSFET		MOSFET	IGBT
HF Transformer	Nano	Nano	Nano	Nano	Nano
60 Hz Transformer	yes	yes			

Risk Level:	Low	Moderate	Considerable	High

DOE Sunshot - SEGIS-AC, ARPA-E

"$1/W Systems: A Grand Challenge for Electricity from Solar"

Workshop, August 10-11, 2010

Goal : 1$/W by 2017

for 5 MW PV Plant

$0.5/W – PV module

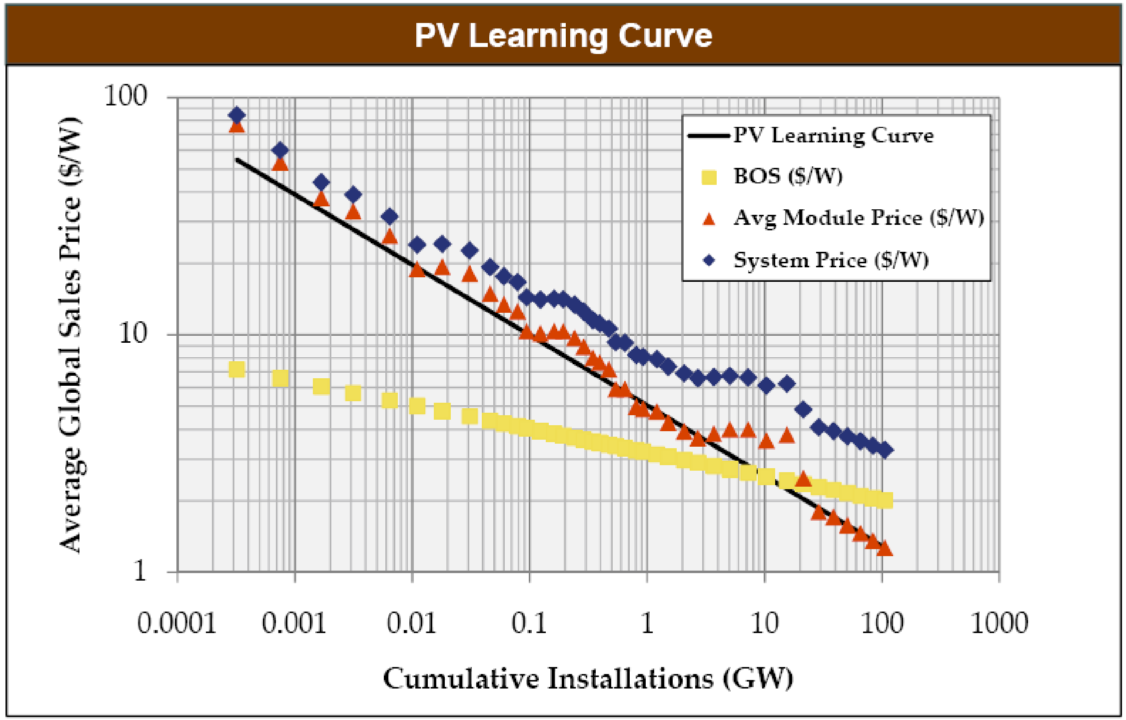
$0.4/W – BOS

$0.1/W – Power electronics

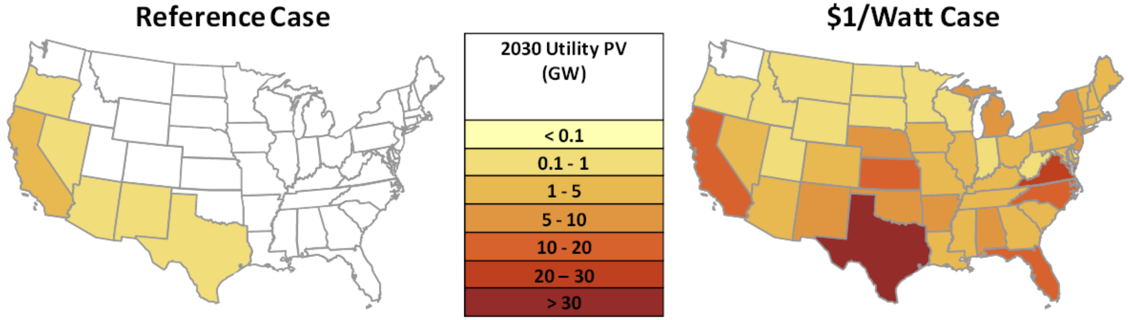
Smart Grid Functionality

High Penetration

Enhanced Grid Value

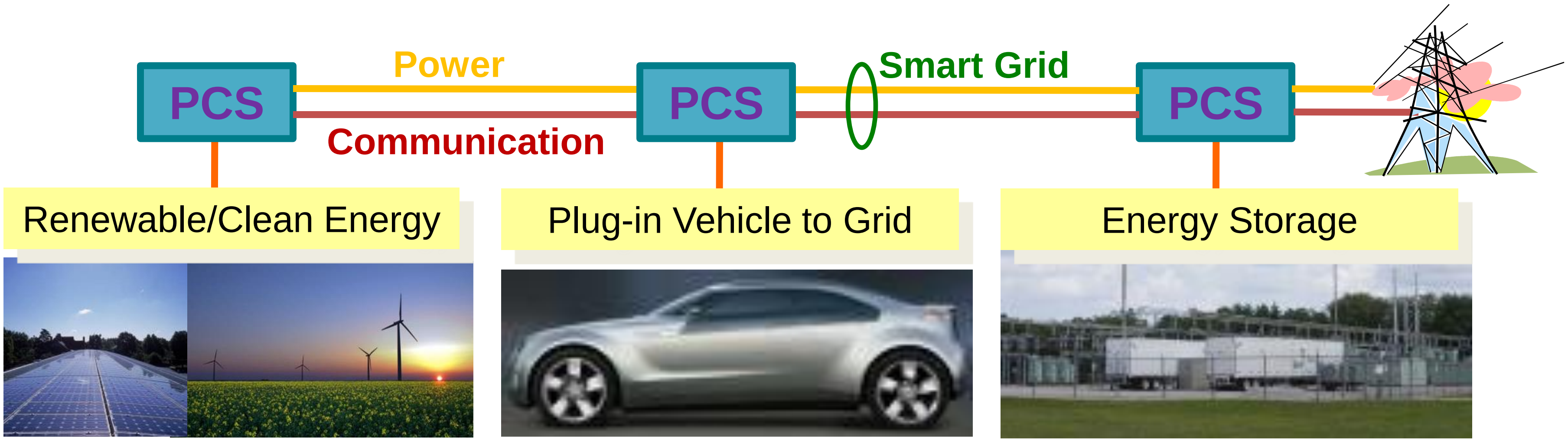


Source: Navigant Consulting



$1/W achieves cost parity in most states!

High Penetration of Distributed Energy Resources

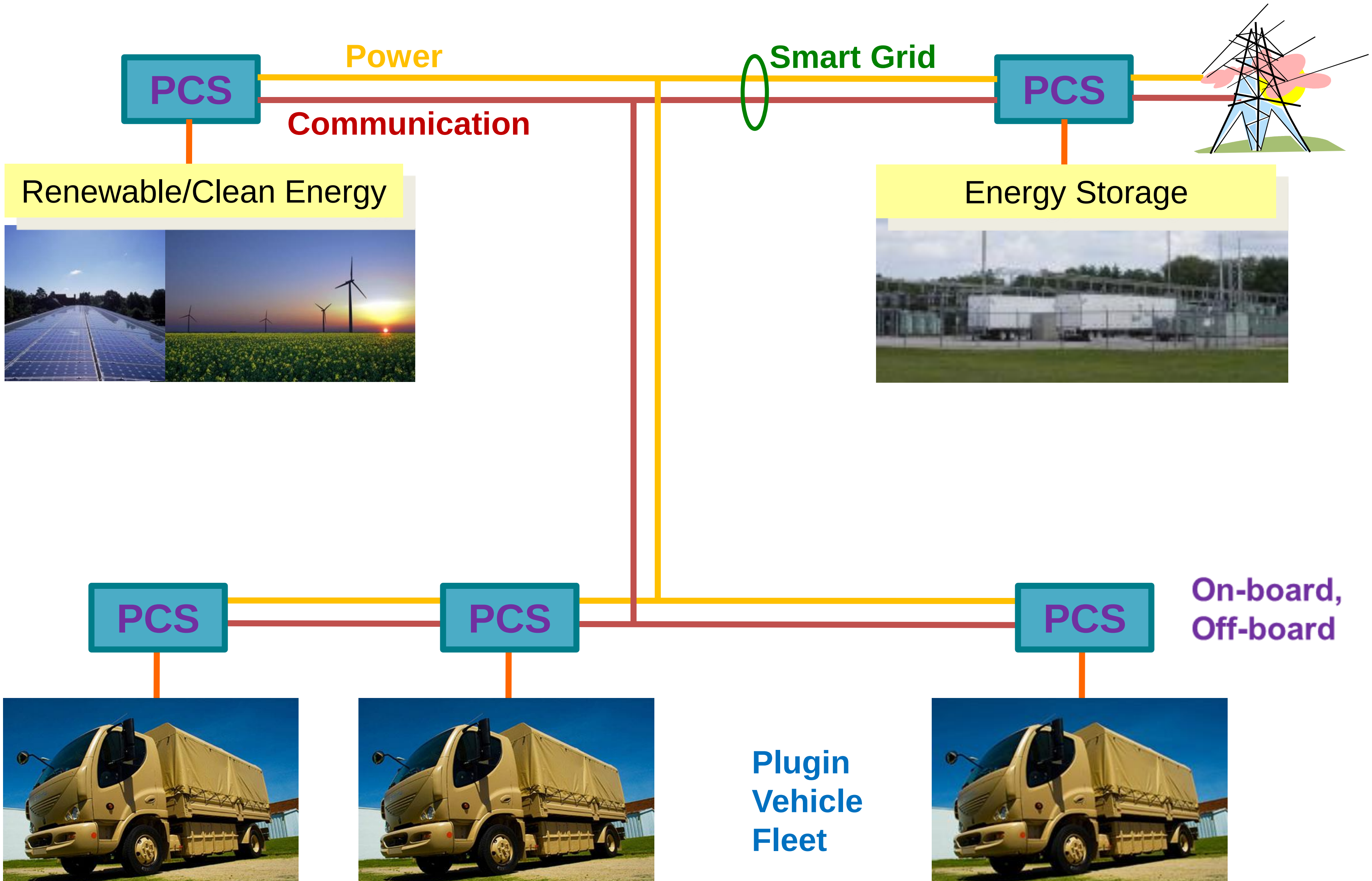


- Power Conditioning Systems (PCS) convert to/from 60 Hz AC for interconnection of renewable energy, electric storage, and PEVs

- "Smart Grid Interconnection Standards" required for devices to be utility-controlled operational asset and enable high penetration:
  - **Dispatchable real and reactive power**
  - **Acceptable ramp-rates to mitigate renewable intermittency**
  - **Accommodate faults faster, without cascading area-wide events**
  - **Voltage/frequency regulation and utility-controlled islanding**

http://www.nist.gov/pml/high_megawatt/2008_workshop.cfm

PCS Architectures for PEV Fleet as Grid Storage



http://www.nist.gov/pml/high_megawatt/jun2011_workshop.cfm

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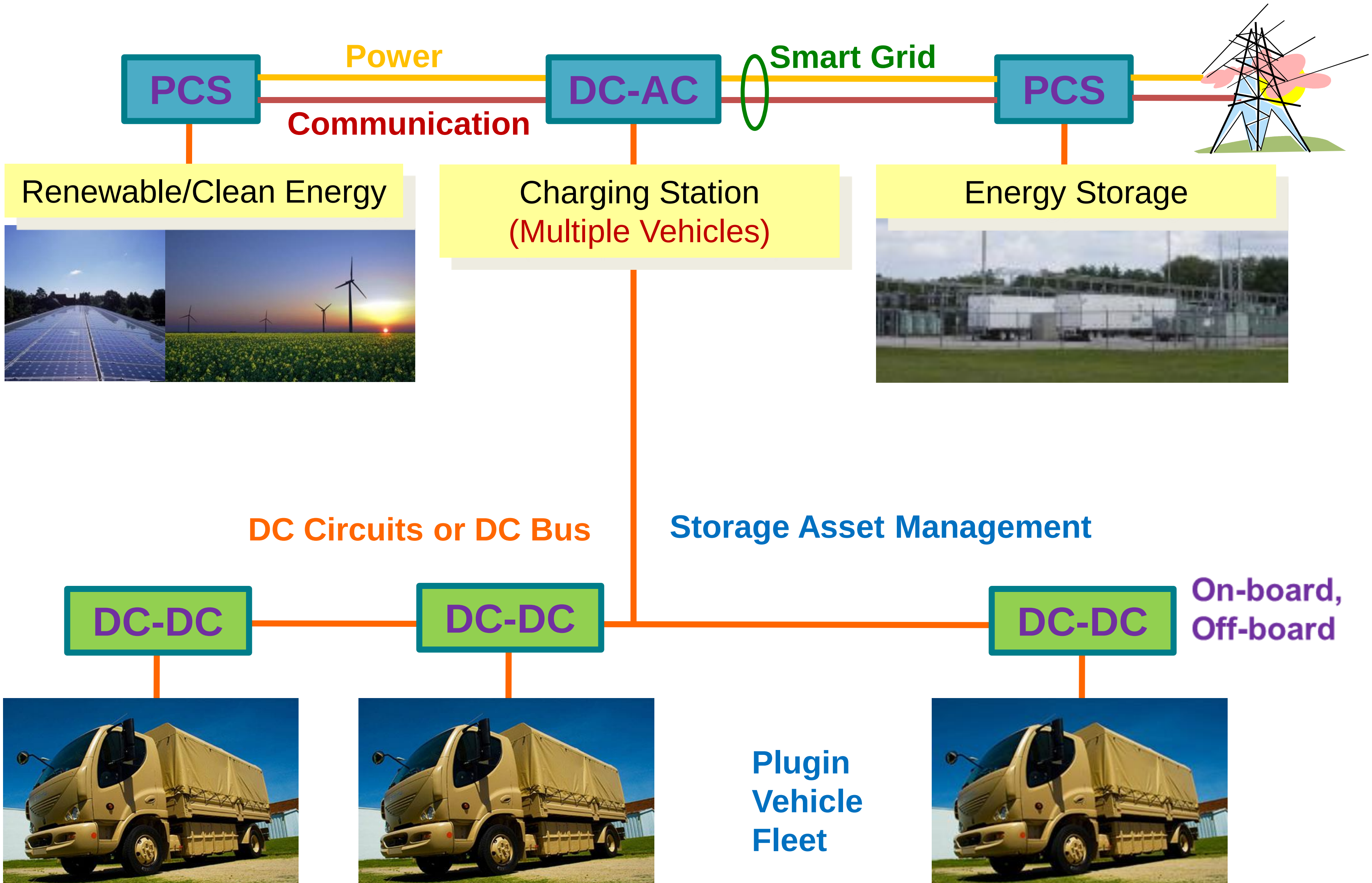
Large Inverter with DC Circuits to Fleet PEVs



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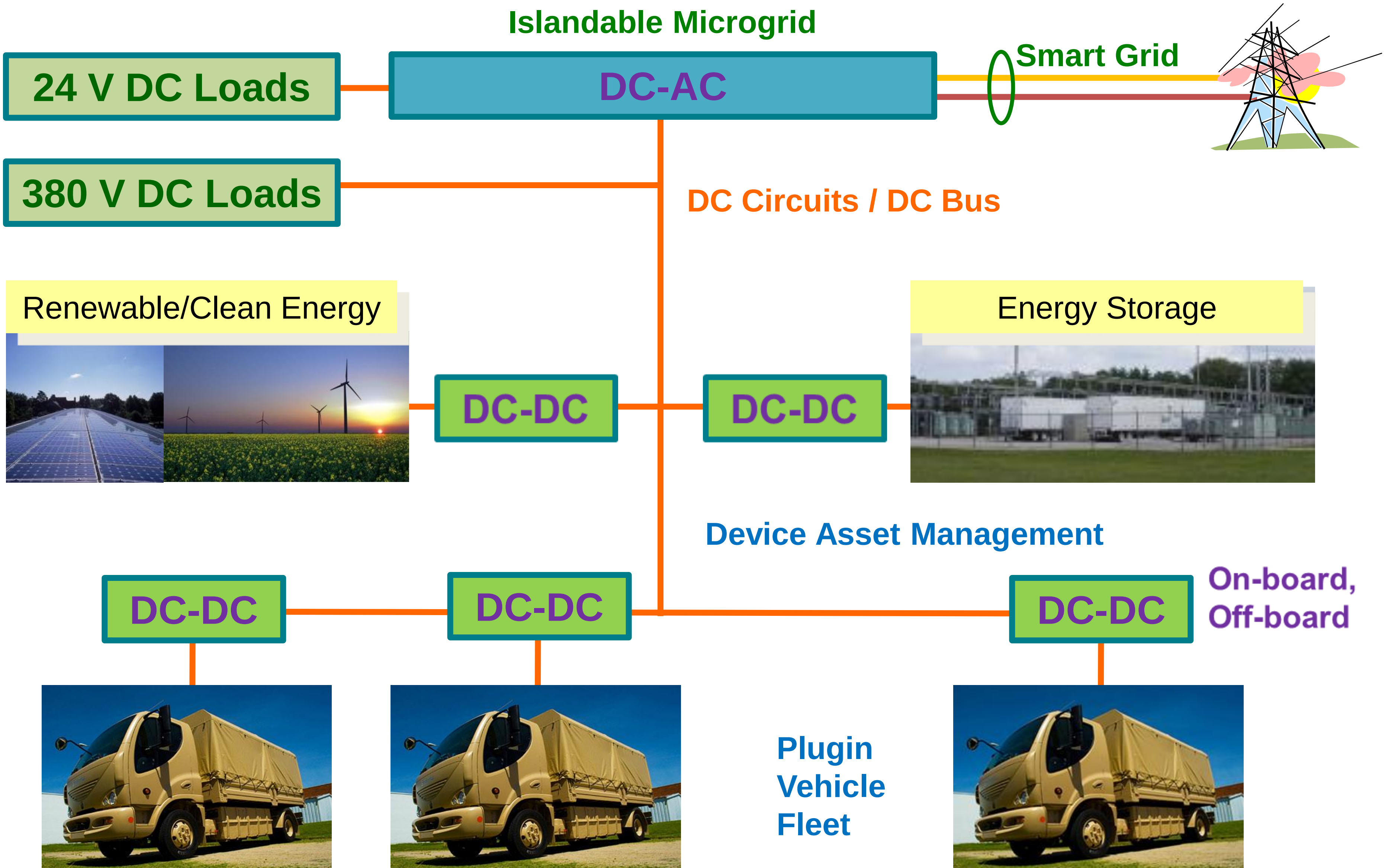
DC Microgrid: DC-AC with DC Circuits



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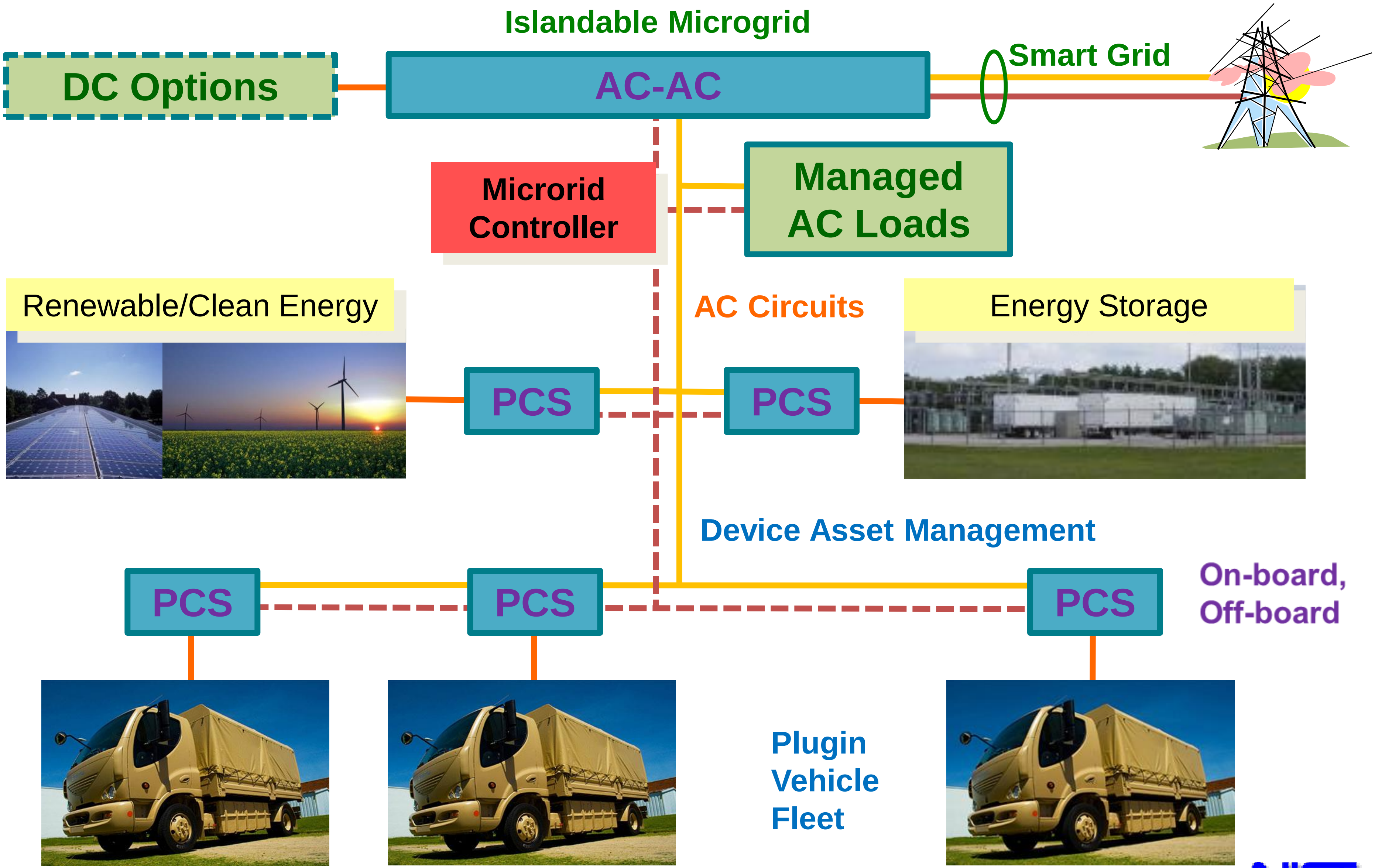
Flow Control Microgrid: AC-AC with AC Circuits



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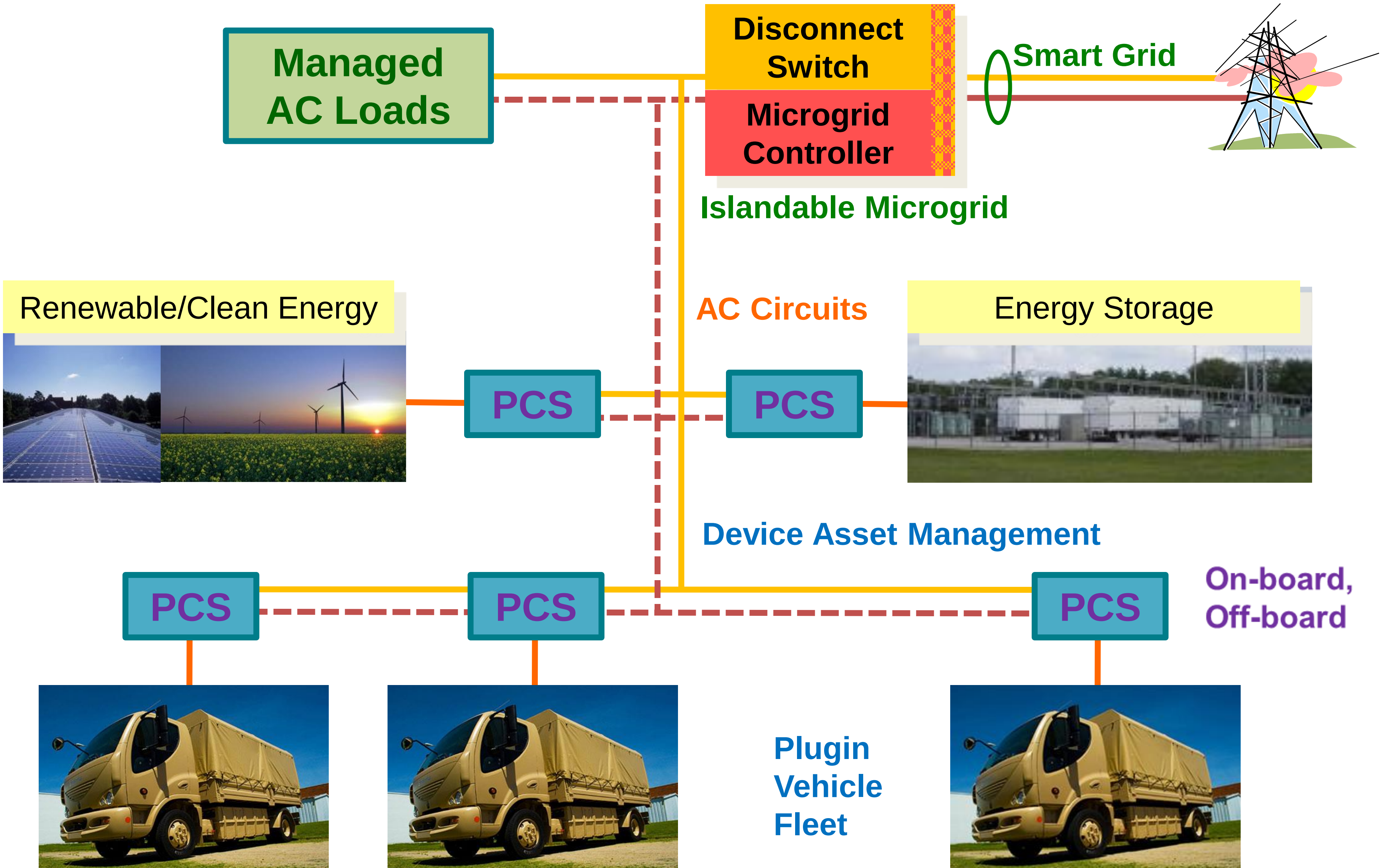
Microgrid using Disconnect and Local EMS



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ECONOMIC BENEFITS OF INCREASING ELECTRIC GRID RESILIENCE TO WEATHER OUTAGES

Executive Office of the President August 2013

”Priority 3: Increase System Flexibility and Robustness”

“Additional transmission lines increase power flow capacity and provide greater control over energy flows. This can increase system flexibility by providing greater ability to bypass damaged lines and reduce the risk of cascading failures. **Power electronic-based controllers can provide the flexibility and speed in controlling the flow of power over transmission and distribution lines.**

Energy storage can also help level loads and improve system stability. Electricity storage devices can reduce the amount of generating capacity required to supply customers at times of high energy demand – known as peak load periods. **Another application of energy storage is the ability to balance microgrids to achieve a good match between generation and load.** Storage devices can provide frequency regulation to maintain the balance between the network's load and power generated. Power electronics and energy storage technologies also support the utilization of renewable energy, whose power output cannot be controlled by grid operators.

A key feature of a microgrid is its ability during a utility grid disturbance to separate and isolate itself from the utility seamlessly with little or no disruption to the loads within the microgrid. Then, when the utility grid returns to normal, the microgrid automatically resynchronizes and reconnects itself to the grid in an equally seamless fashion. Technologies include advanced communication and controls, building controls, and distributed generation, including combined heat and power which demonstrated its potential by keeping on light and heat at several institutions following Superstorm Sandy.”

Smart Grid – U.S. National Priority

"We'll fund a better, smarter electricity grid and train workers to build it…"
President Barack Obama

"To meet the energy challenge and create a 21st century energy economy, we need a 21st century electric grid…" ***Secretary of Energy Steven Chu***

"A smart electricity grid will revolutionize the way we use energy, but we need standards …" ***Secretary of Commerce Gary Locke***

Congressional Priority: EISA 2007, ARRA, oversight, new bills …

Administration Priority – *www.whitehouse.gov/ostp/*

- A Policy Framework for the 21st Century Grid (June 2011)
- Green Button Initiative – available to 35 Million by 2013 – *www.nist.gov/smartgrid/greenbutton.cfm*

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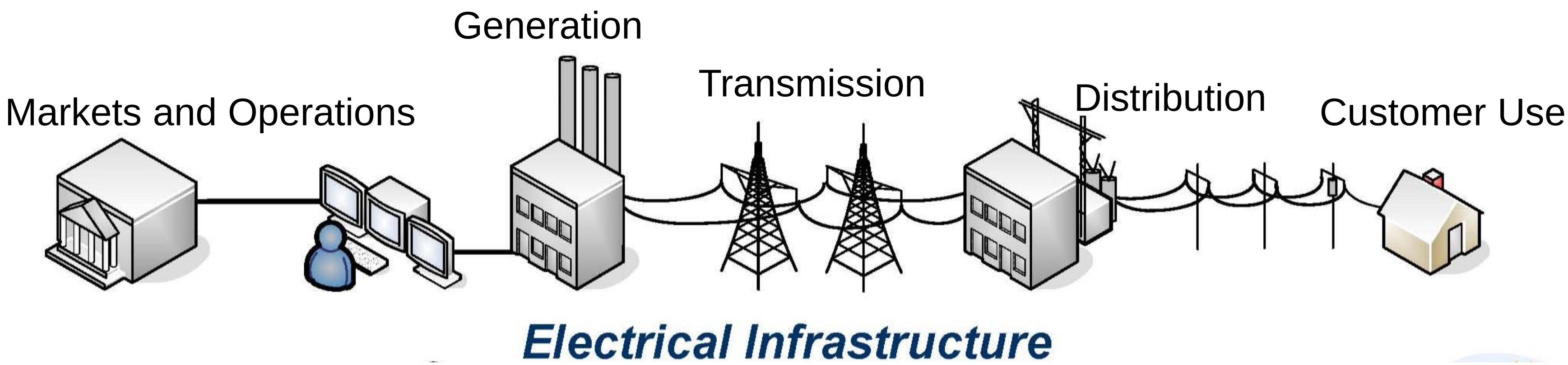
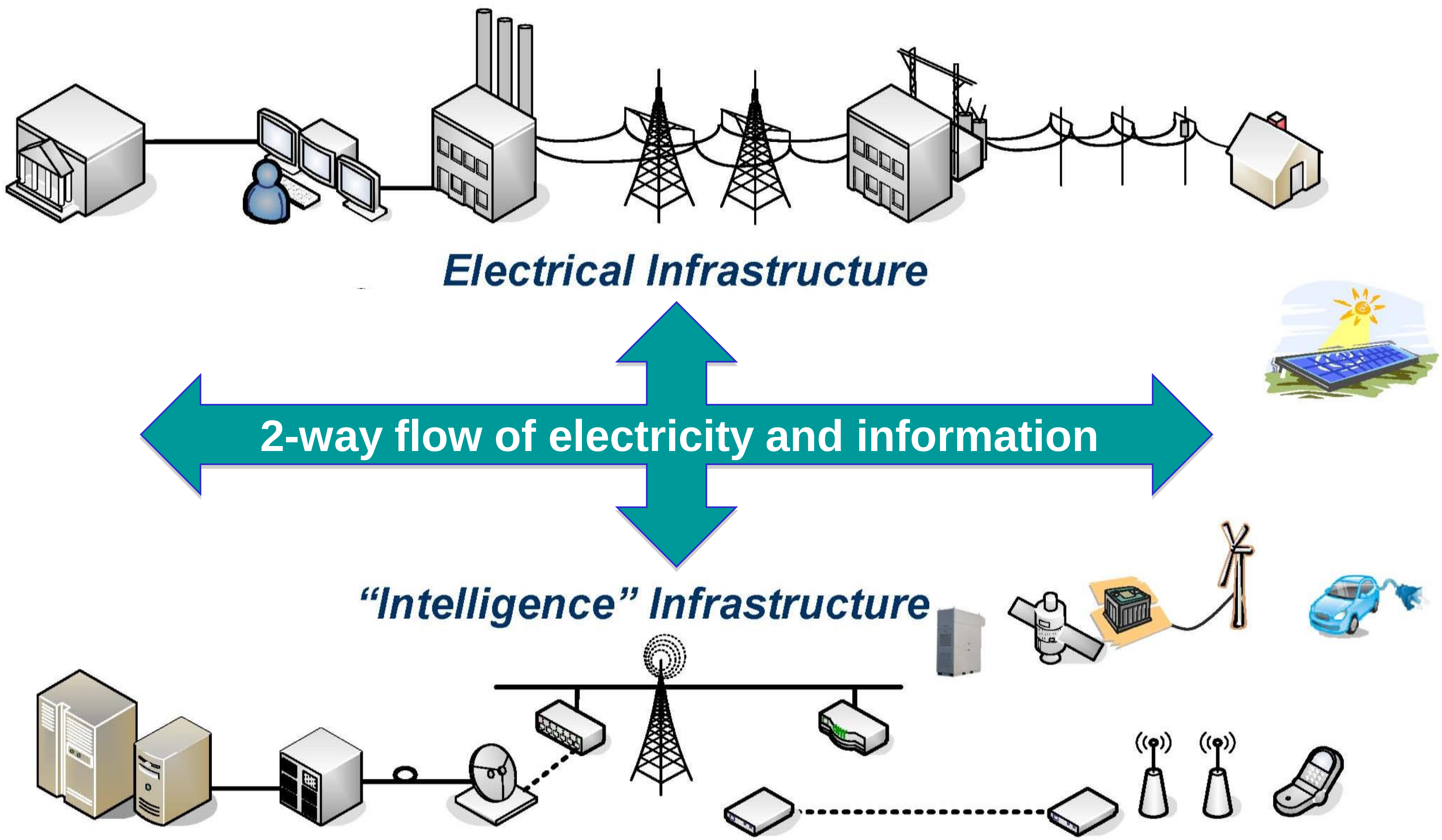
Today's Electric Grid



One-way flow of electricity

Centralized, bulk generation
Heavy reliance on coal, natural gas
Limited automation
Limited situational awareness
Consumers lack data to manage energy usage

Smart Grid = Electrical Grid + Intelligence



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NIST Role in Smart Grid

Energy Independence and Security Act (2007)

In cooperation with the DoE, NEMA, IEEE, GWAC, and other stakeholders, **NIST** has "primary responsibility to **coordinate development of a framework** that includes protocols and model standards for information management **to achieve interoperability of smart grid devices and systems**…"

http://sgip.org

http://www.nist.gov/smartgrid/

The Smart Grid

White House Kickoff Meeting

- May 18, 2009: Meeting chaired by Secretaries of Energy and Commerce
- 66 CEOs and senior executives, federal and state regulators

- Commitment of industry CEOs for their people (staff) to participate in NIST process to accelerate development of a smart grid roadmap

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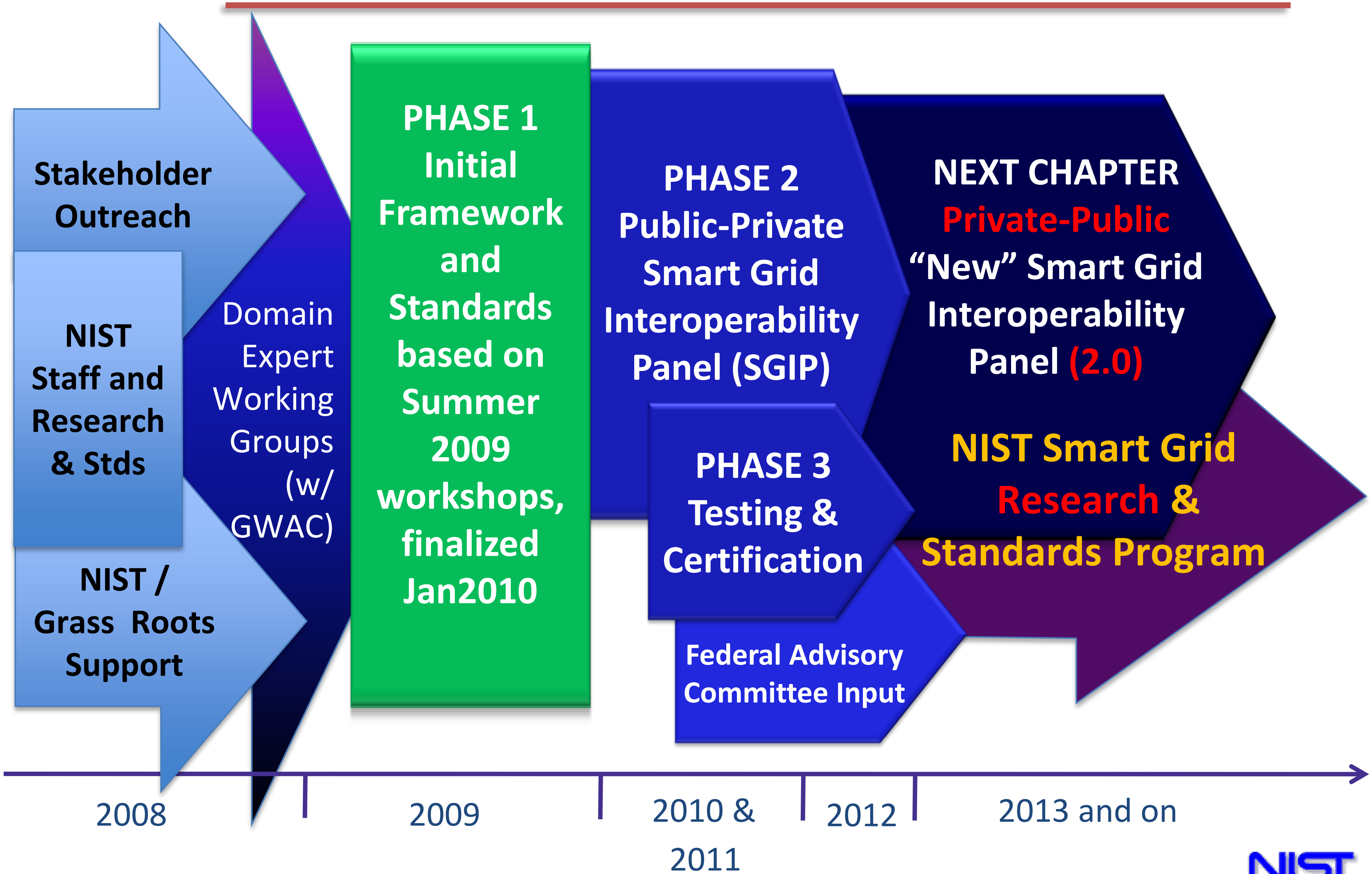
NIST Smart Grid Interoperability Plan



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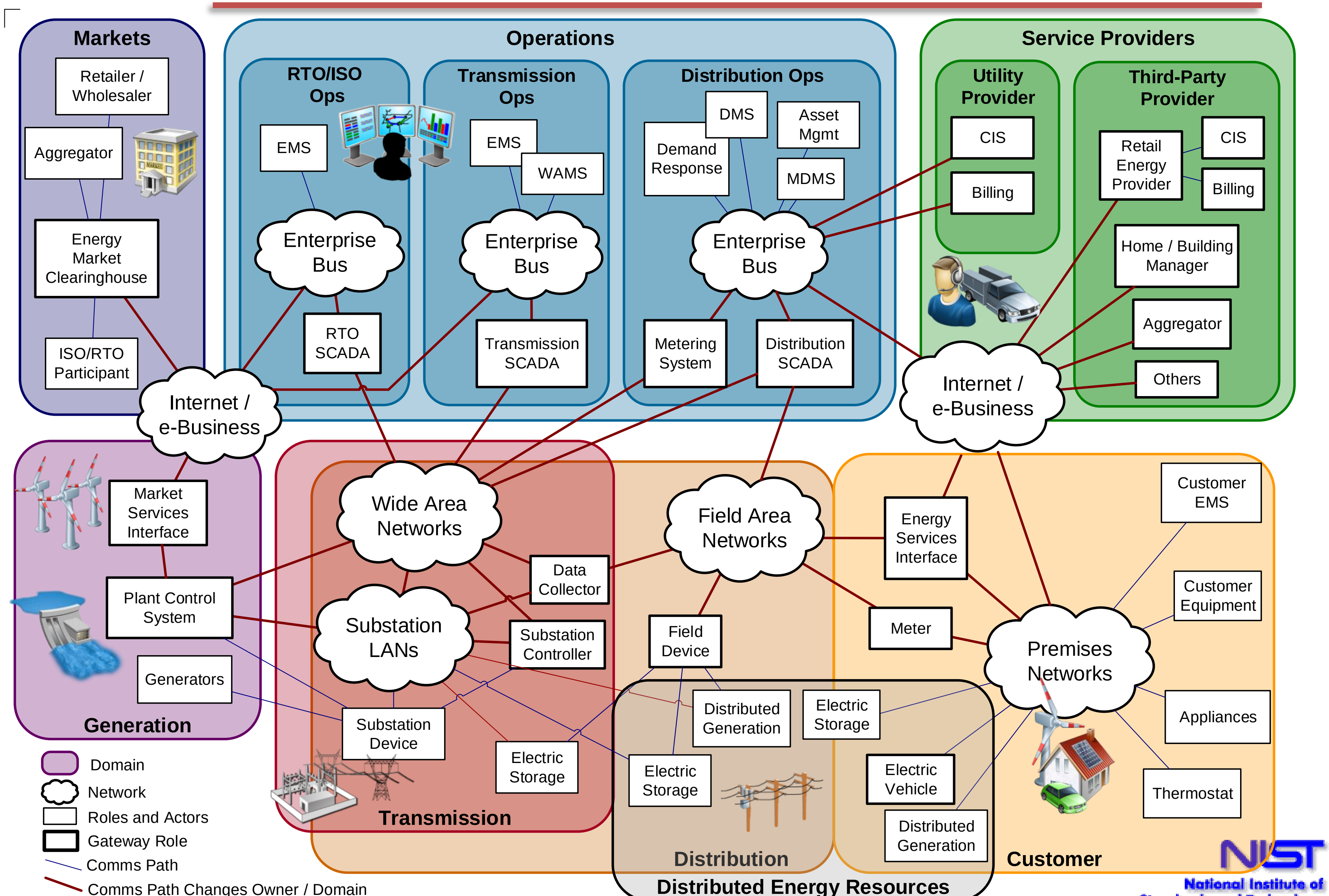
NIST SG Framework and Roadmap 3.0 Draft

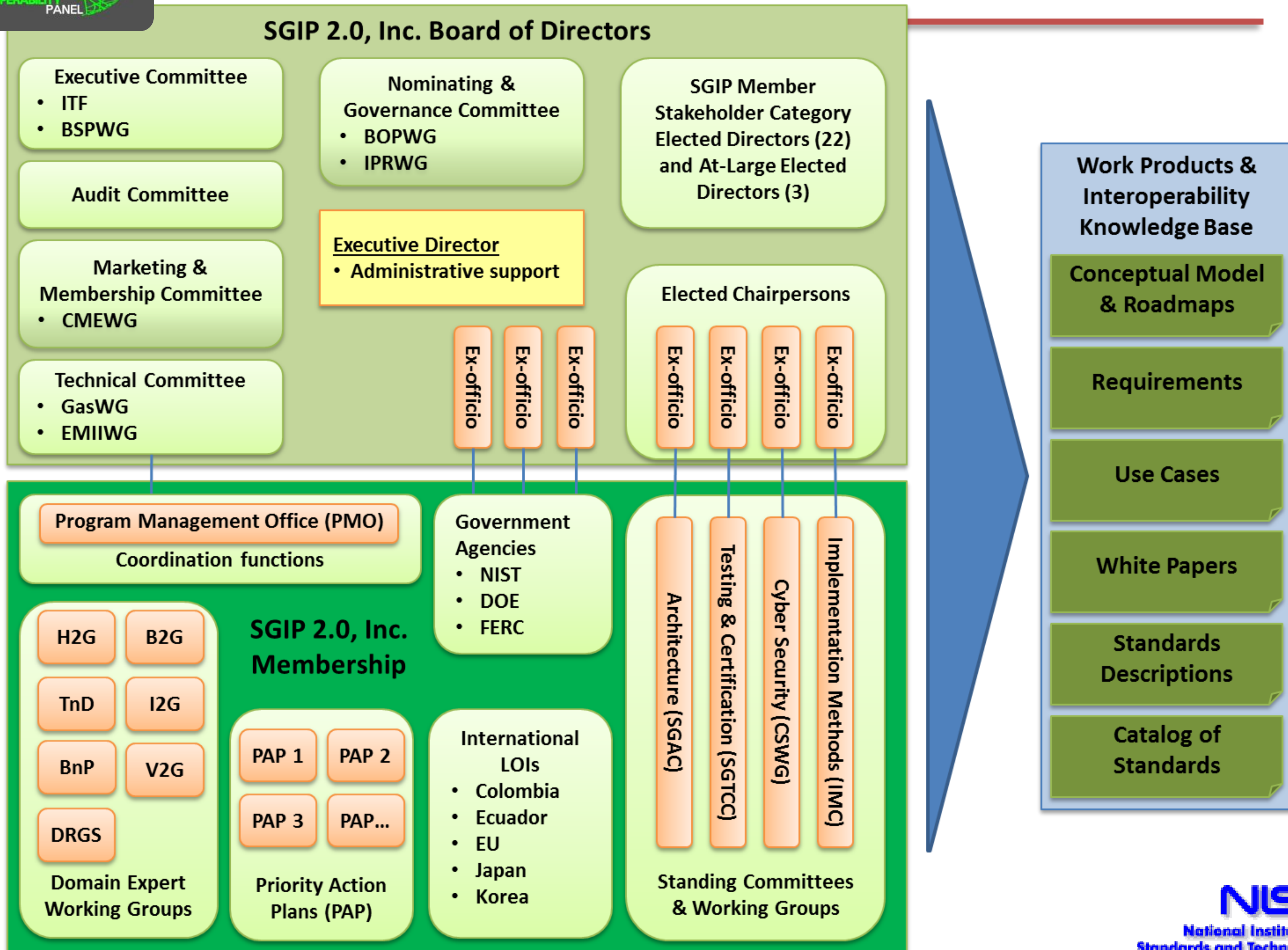
Applications and Requirements - Nine Priority Areas:

- Demand response and consumer energy efficiency
- Wide-area situational awareness
- Distributed Energy Resources (DER)
- Energy storage
- Electric transportation
- Network communications
- Advanced metering infrastructure (AMI)
- Distribution grid management
- Cybersecurity

NIST SG Architecture Reference Model



SGIP 2.0 Inc, Organization (Draft)



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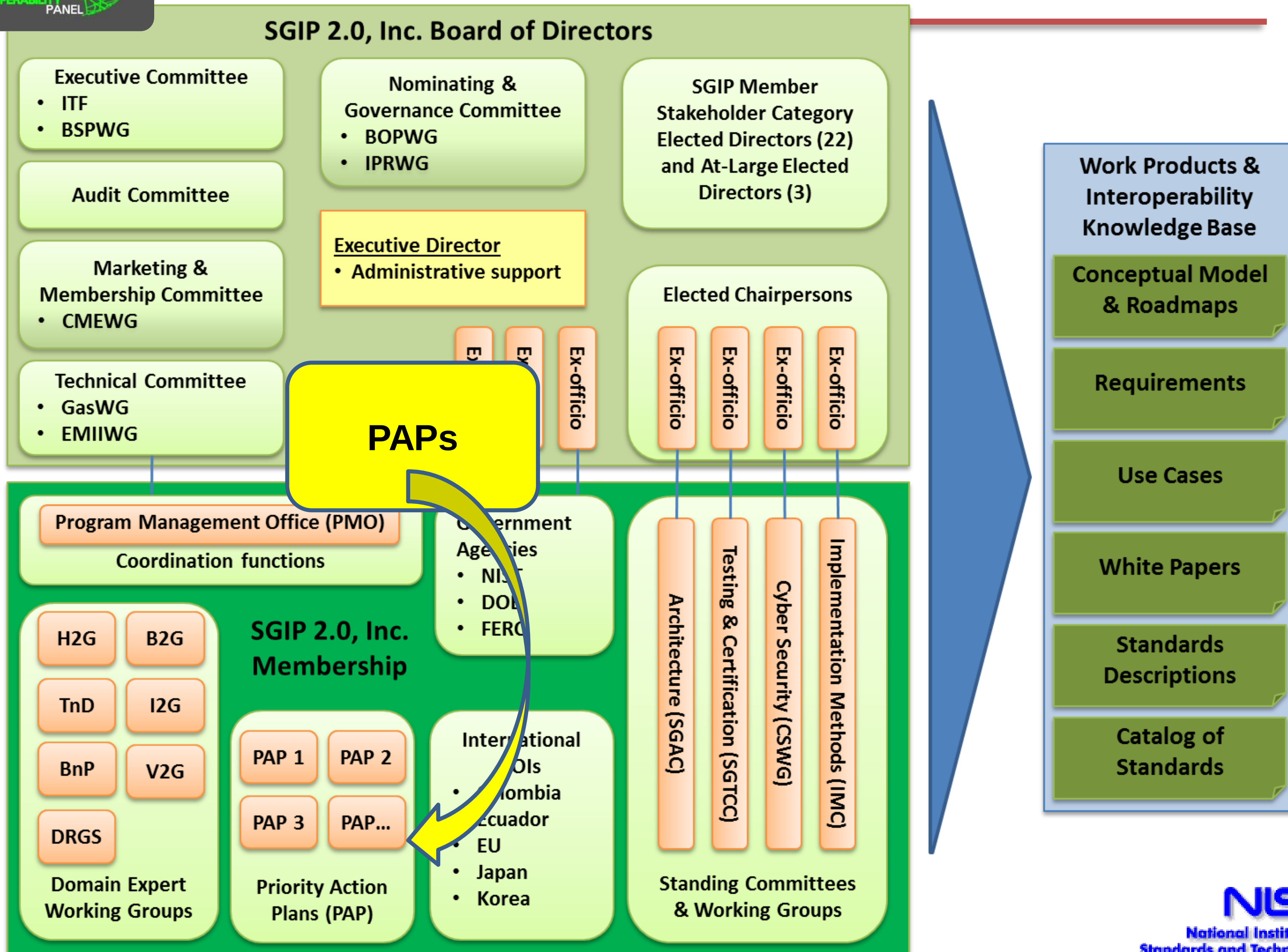

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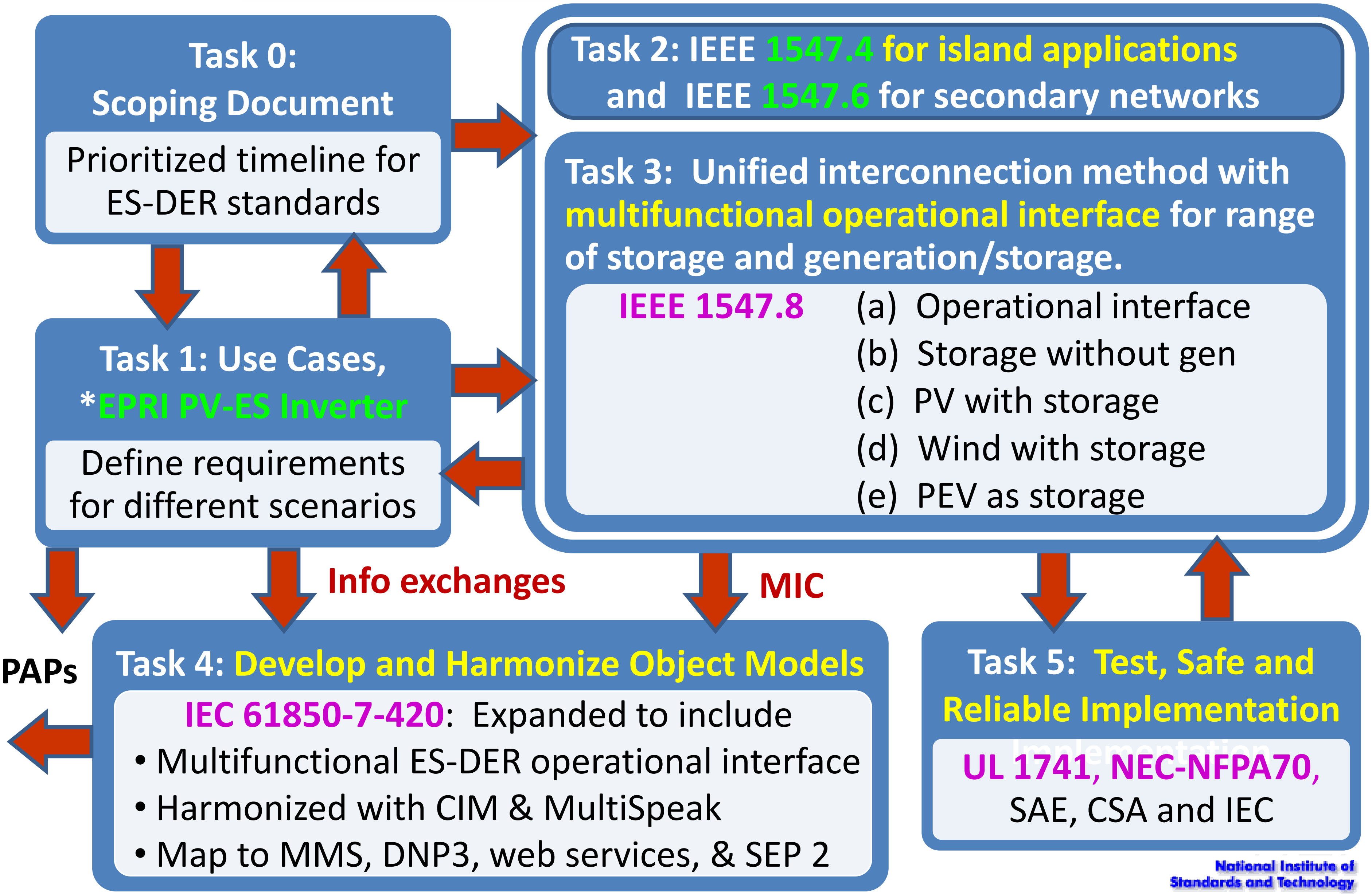
SGIP SMART GRID INTEROPERABILITY PANEL

PAP 7: Smart Grid ES-DER Standards



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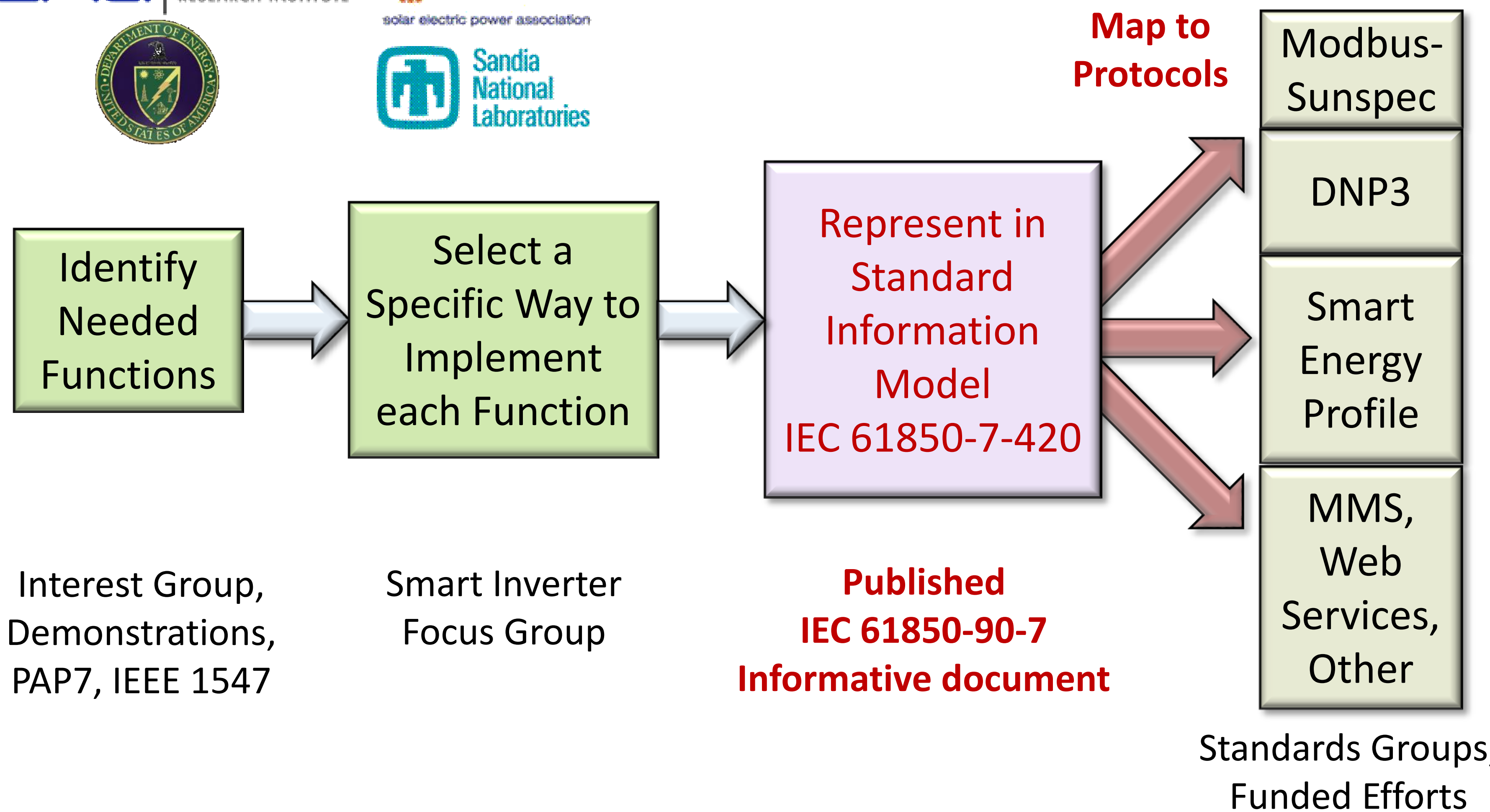
EPRI/Sandia NL Smart Inverter Initiative



courtesy: Brian Seal (EPRI)

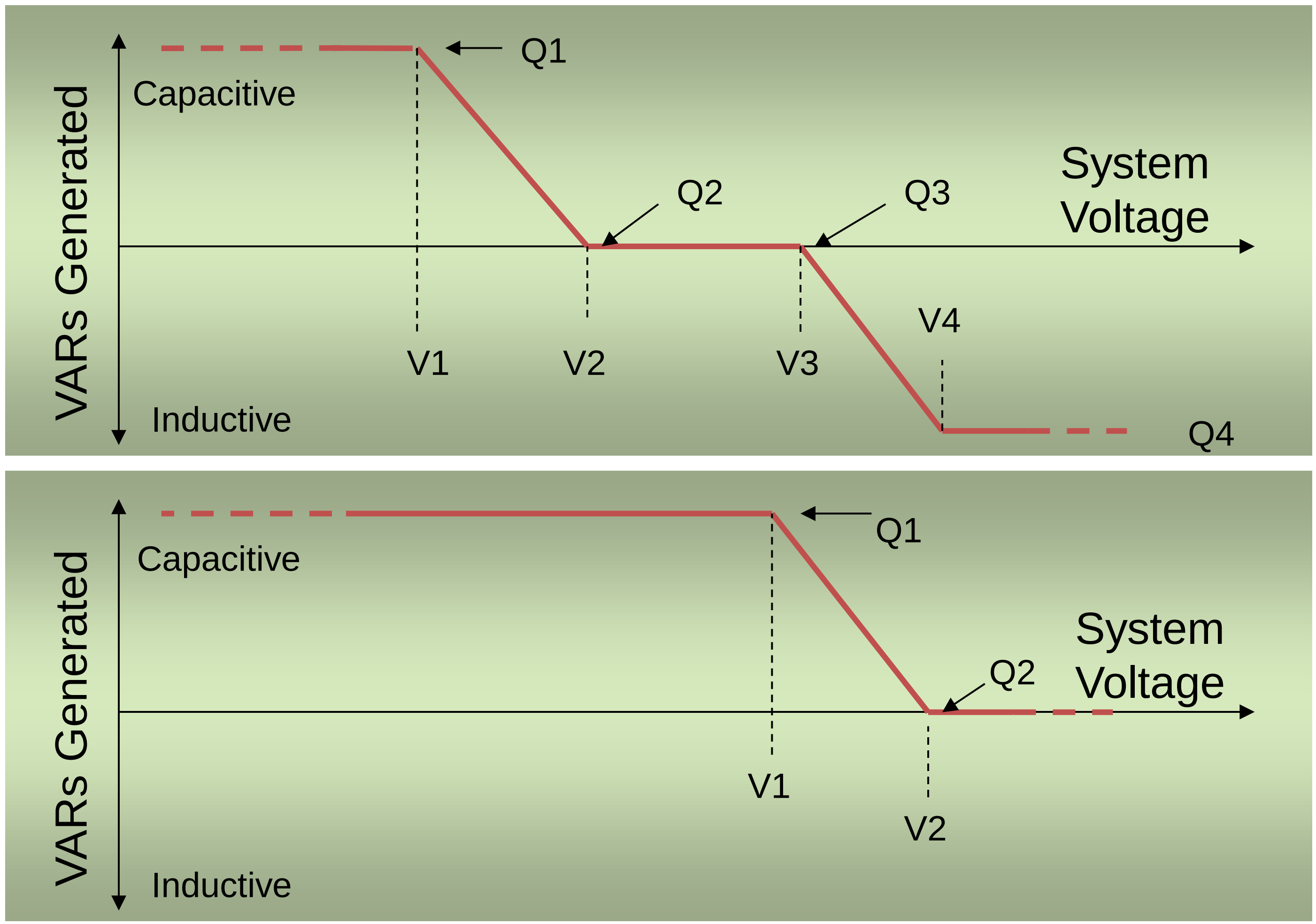
EPRI/SNL Volt-Var Control Function

Utility-Defined Curve Shapes

Volt/Var Mode 1 – Normal Regulation

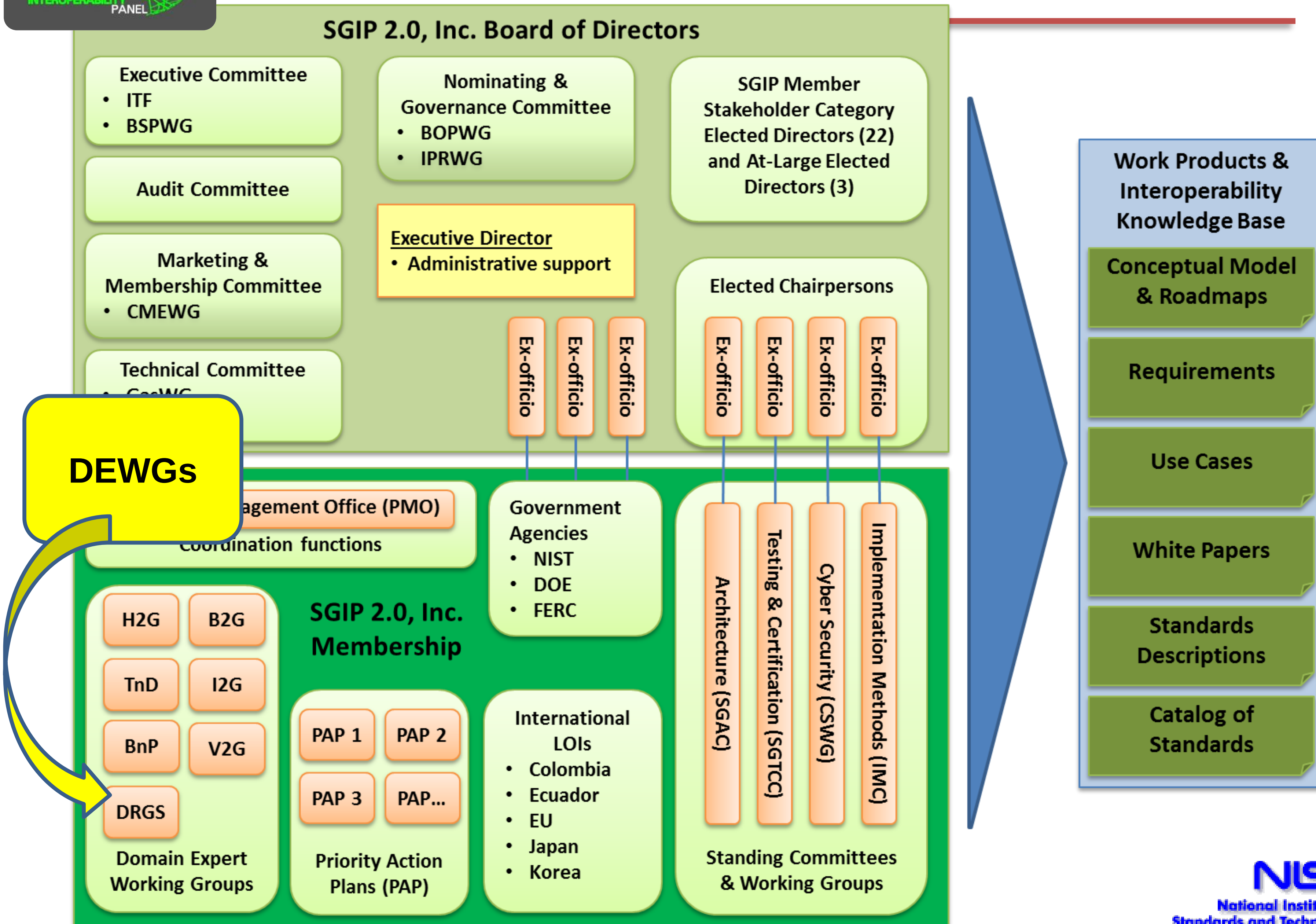
Simple Broadcast

Volt/Var Mode 2 – Transmission VAR Support



courtesy: Brian Seal (EPRI)

SGIP 2.0 Inc, Organization (Draft)



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SGIP SMART GRID INTEROPERABILITY PANEL

Distributed Renewables, Generators and Storage

- DRGS Domain Expert Working Group initiated September 2011
- Identify Smart Grid standards and interoperability issues/gaps for
  - Integration of renewable/clean and distributed generators and storage
  - Operation in high penetration scenarios, weak grids, **microgrids**, **DC grids**
  - Including interaction of high-bandwidth and high-inertia type devices
- Focus on Smart Grid functions that
  - mitigate impact of variability and intermittency of renewable generators
  - enable generators and storage to provide valuable grid supportive services
  - prevent unintentional islanding and cascading events for clustered devices
- Activities of DRGS DEWG
  - Consistent approaches for generators/storage types and domains
  - Use cases and information exchange requirements
  - Define new PAPs to address standards gaps and issues
- Subgroups: A, B, C, D, E, and F

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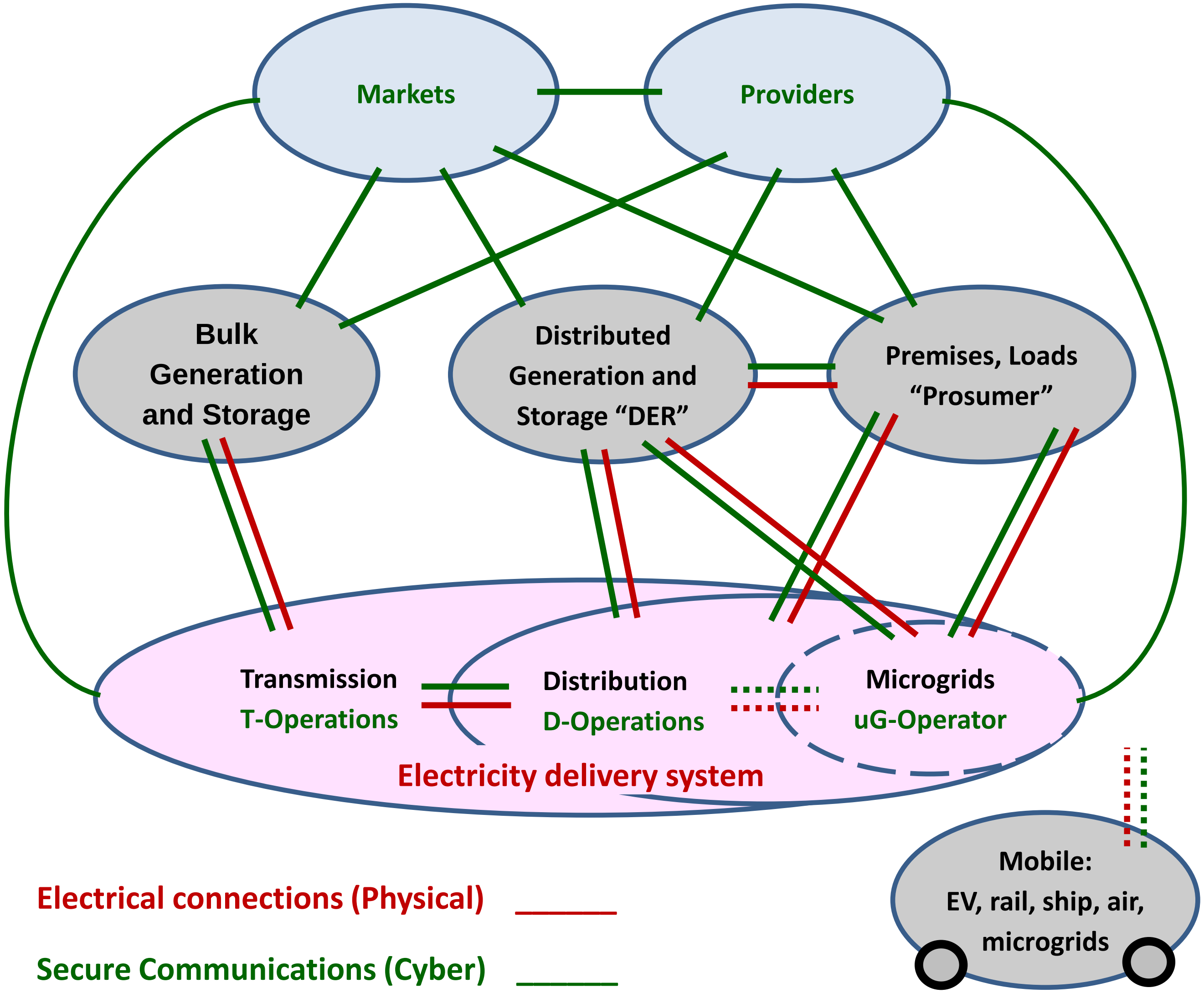
DRGS DEWG Activities

- **DRGS Subgroups:**
  - A. Standards Roadmap – Al Hefner
  - B. UCs, Information Exchange, and Object Models – Frances Cleveland
  - C. Micrograids and Hierarchical Distributed Control – Jim Reilly
  - D. Conformity and Interoperability Test and Certification
    - – Robert Broderick
    - – Ward Bower
  - E. Regulatory and Market Issues – Amanda Stallings
  - F. DER Interconnection Standards – Tom Basso
  - ➢ Weather Information PAP – Al Hefner

- **Special Topics**
  - – Hierarchical Classification of DER Use Cases
  - – Information Support for Integration of Microgrids into Grid Operation
  - – California Rule 21 Updates for Smart Inverters
  - – Regulatory Issues for Microgrid Development

Cyber-Physical Architecture Reference for Resilient/Transactive Power Systems



Electrical connections (Physical) ______

Secure Communications (Cyber) ______

Al Hefner 091713

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Smart u-Grid PCS Testing

SGIP Smart Grid Interoperability

NIST Measurement Science

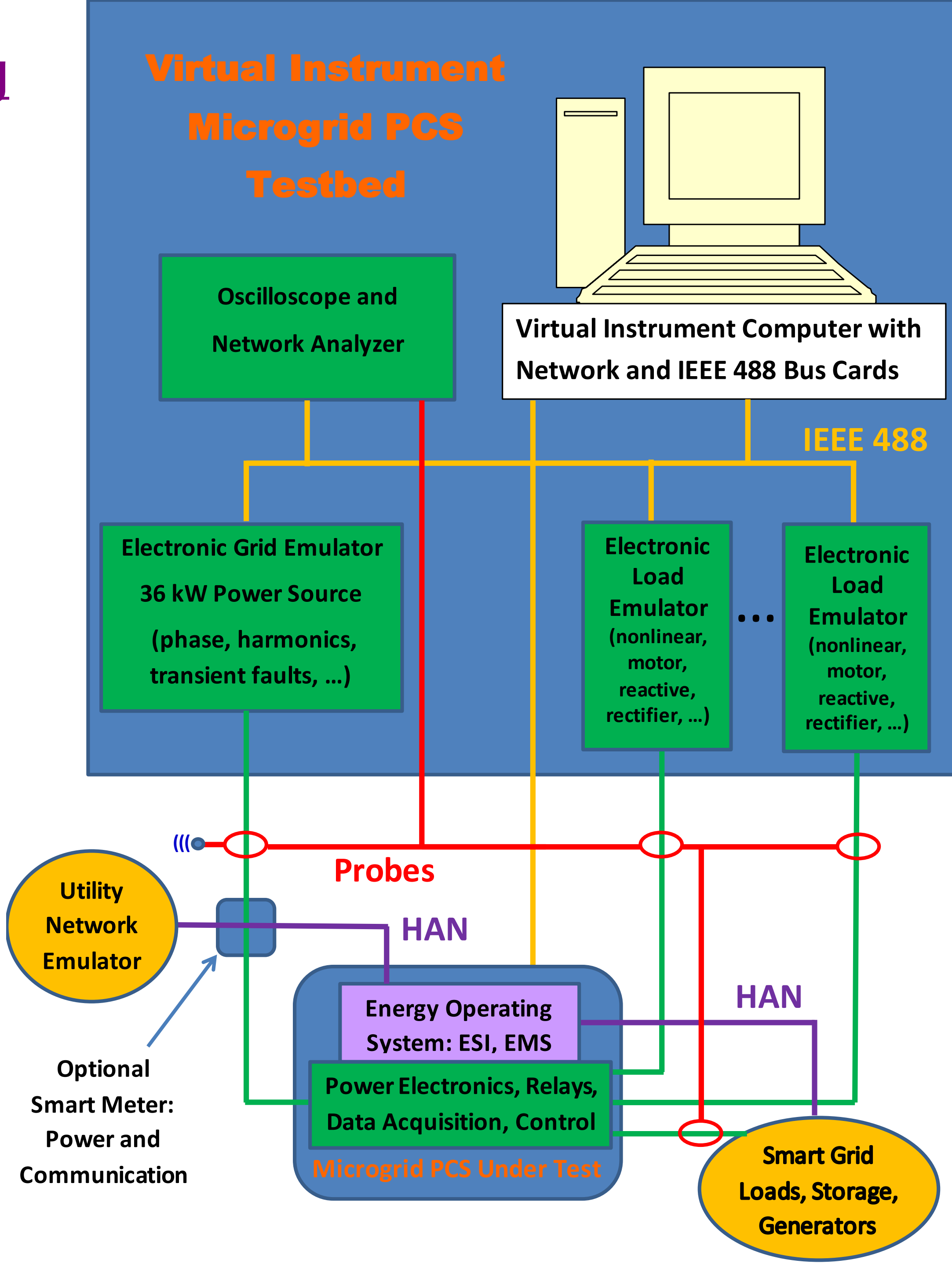
DOE/DOD Labs, Test & Certification

ESI, EMS, Microgrid & Storage functions

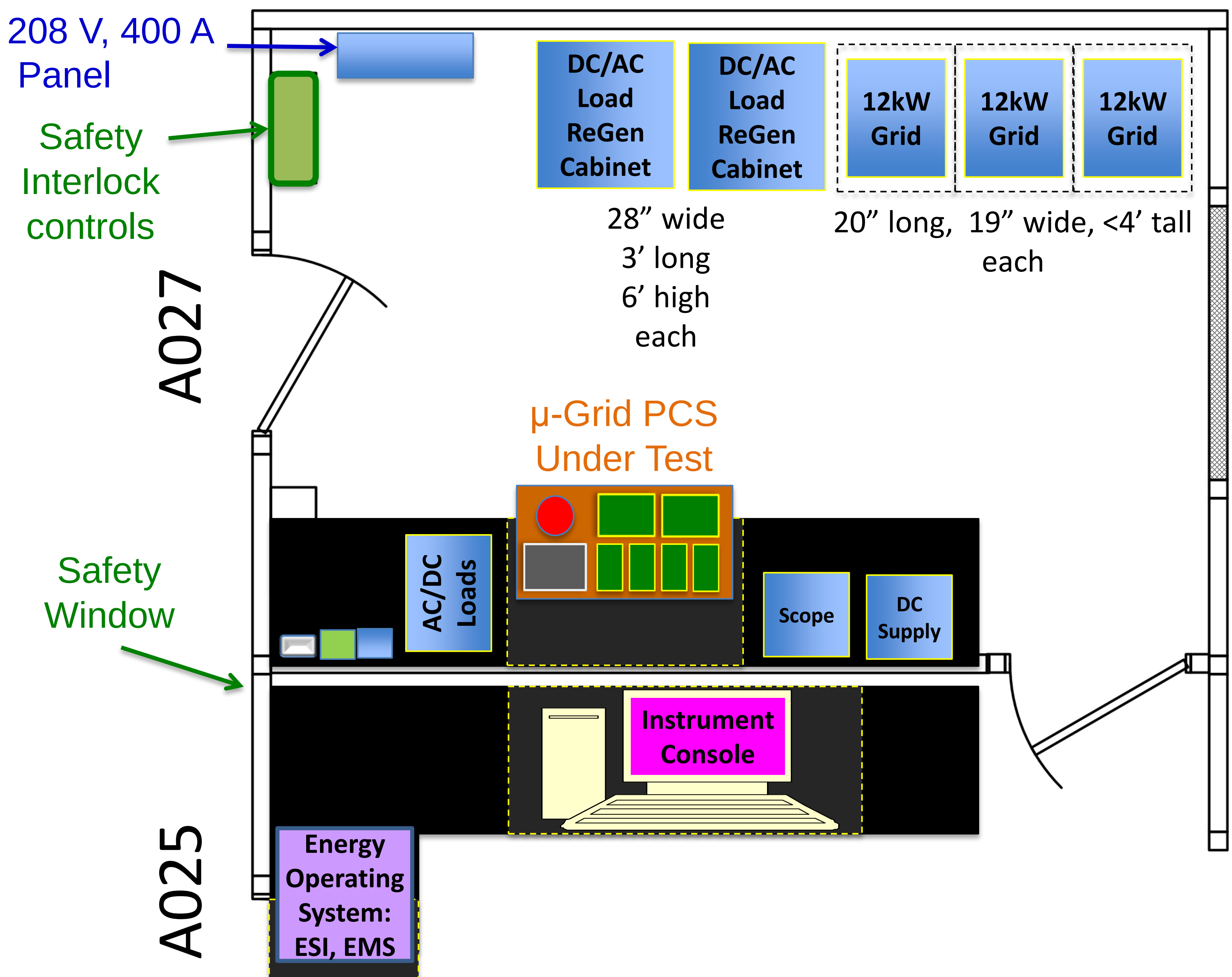
Sensors, IT Networks & meter stds.

NIST Power Electronics Technologies

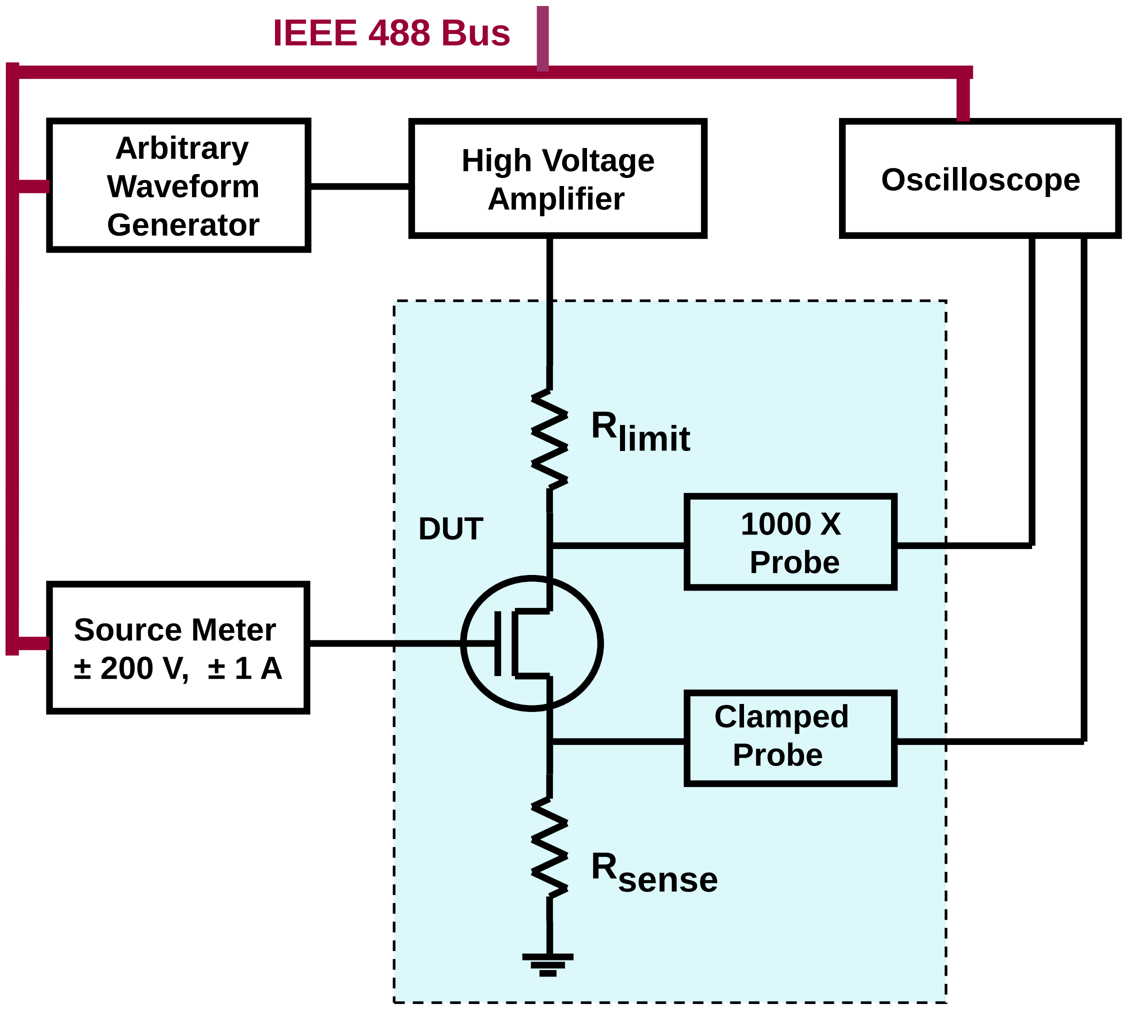
Grid-Interactive DER functions & Energy appliances



Smart Microgrid PCS Lab



25 kV Curve Tracer Schematic

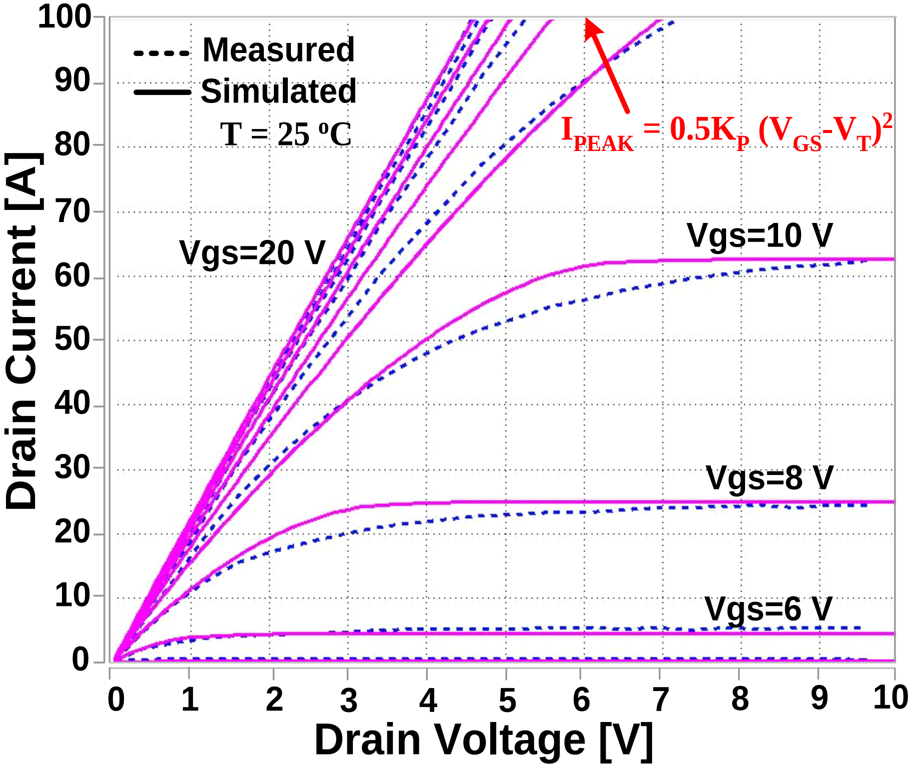


HV safety interlocks

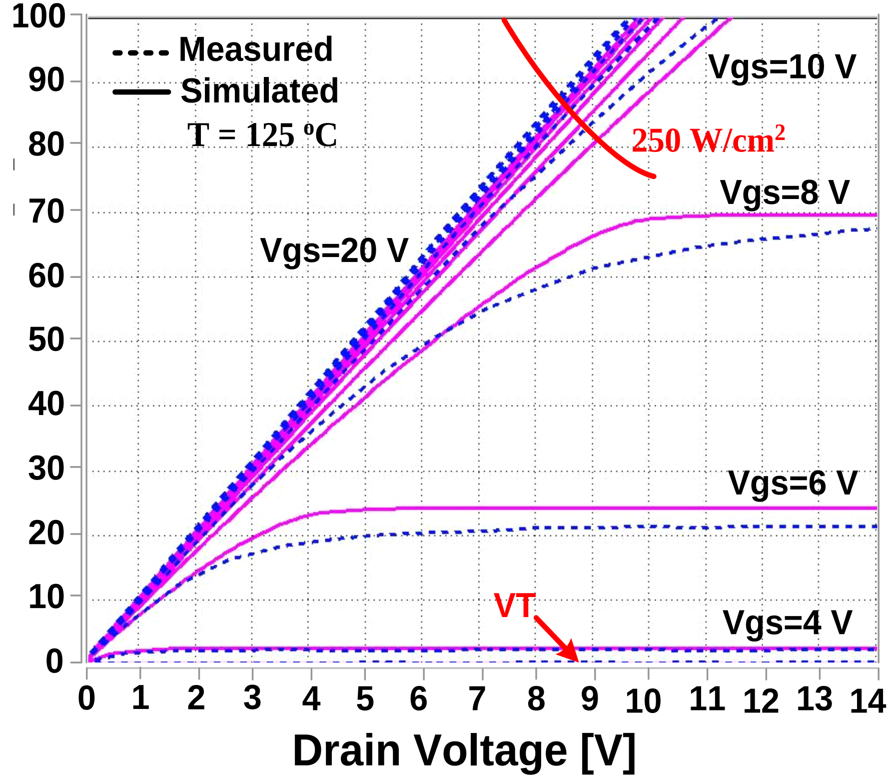
Model Validation for 100 A, 10 kV SiC Power MOSFET

active area = 3 cm^2

25 °C

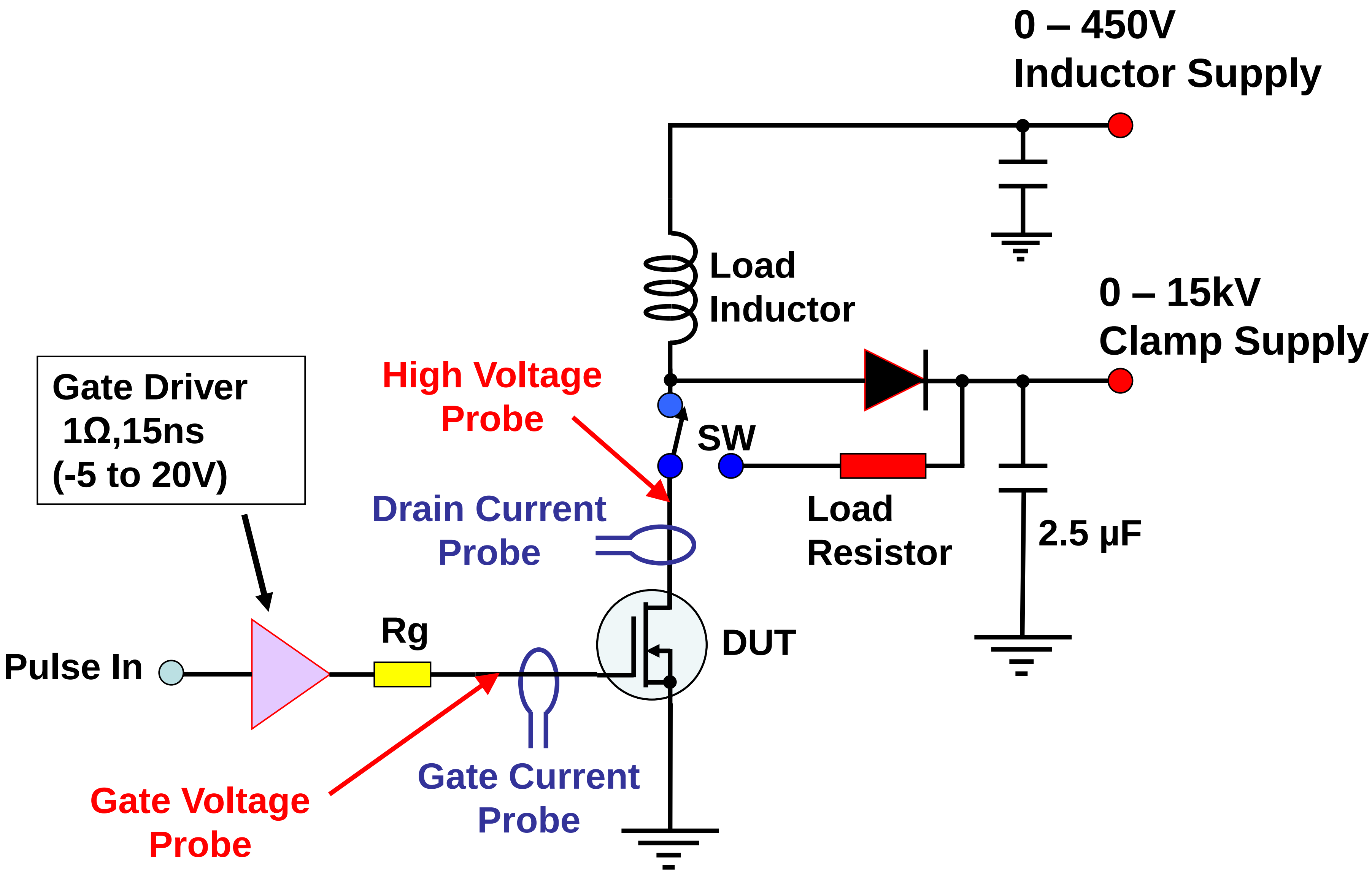


125 °C



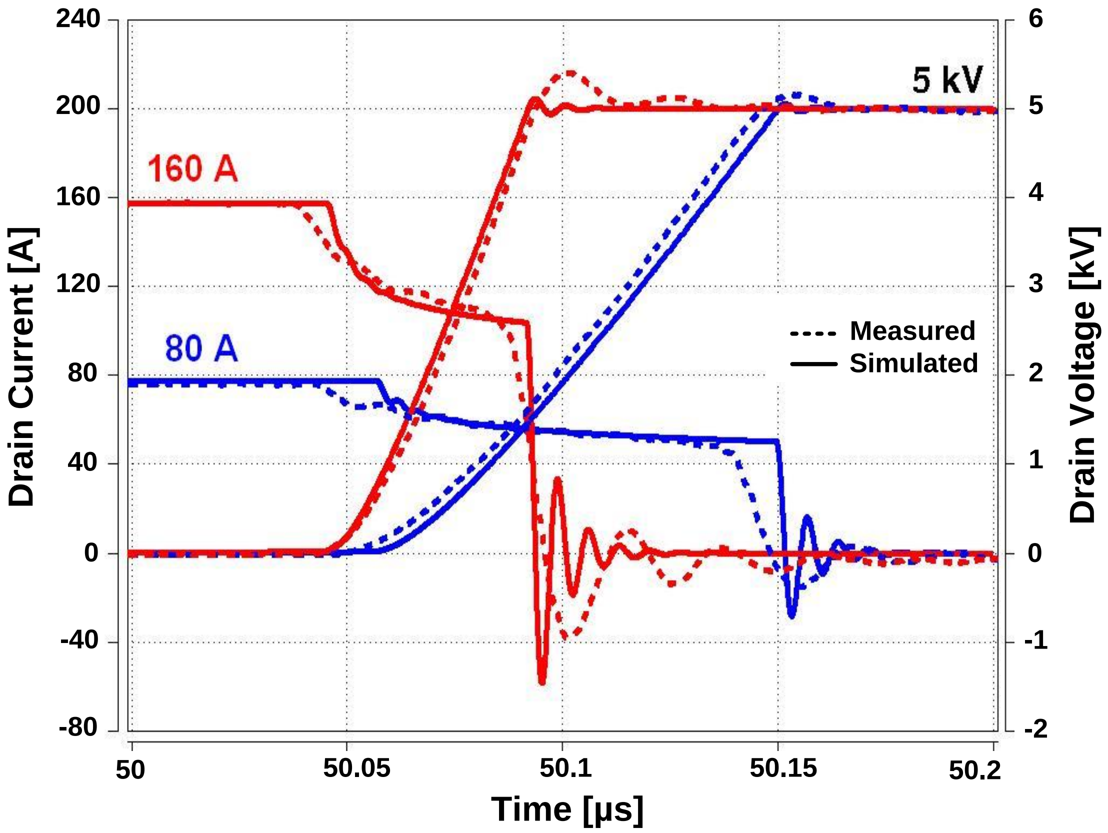
* Dashed curves based on area scaling of 10 A die to 100 A multi-chip module.

HV-HF Switching Test Circuit



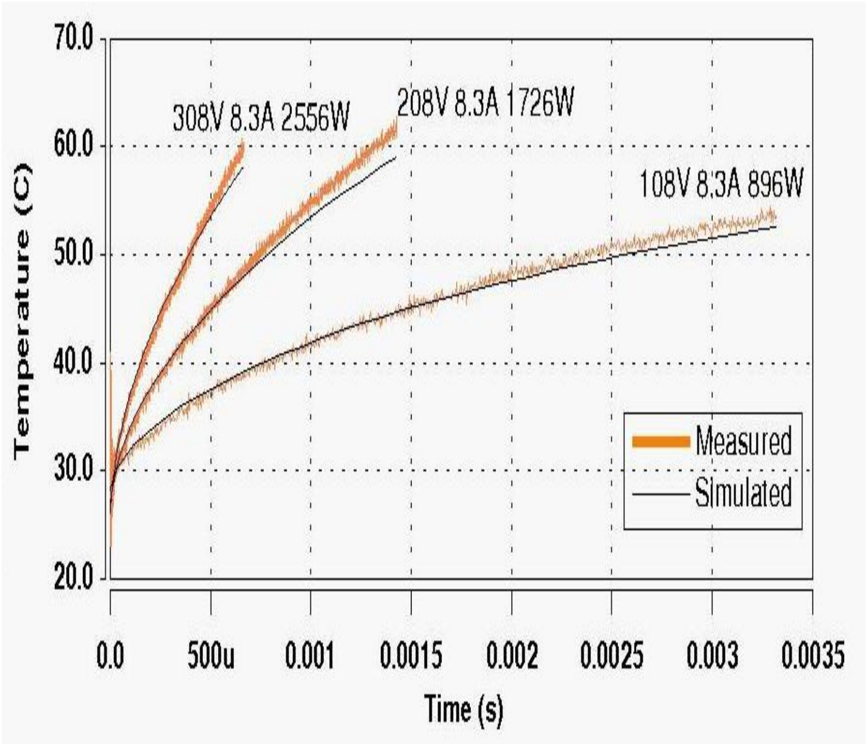
Model Validation for 100 A, 10 kV SiC Power MOSFET

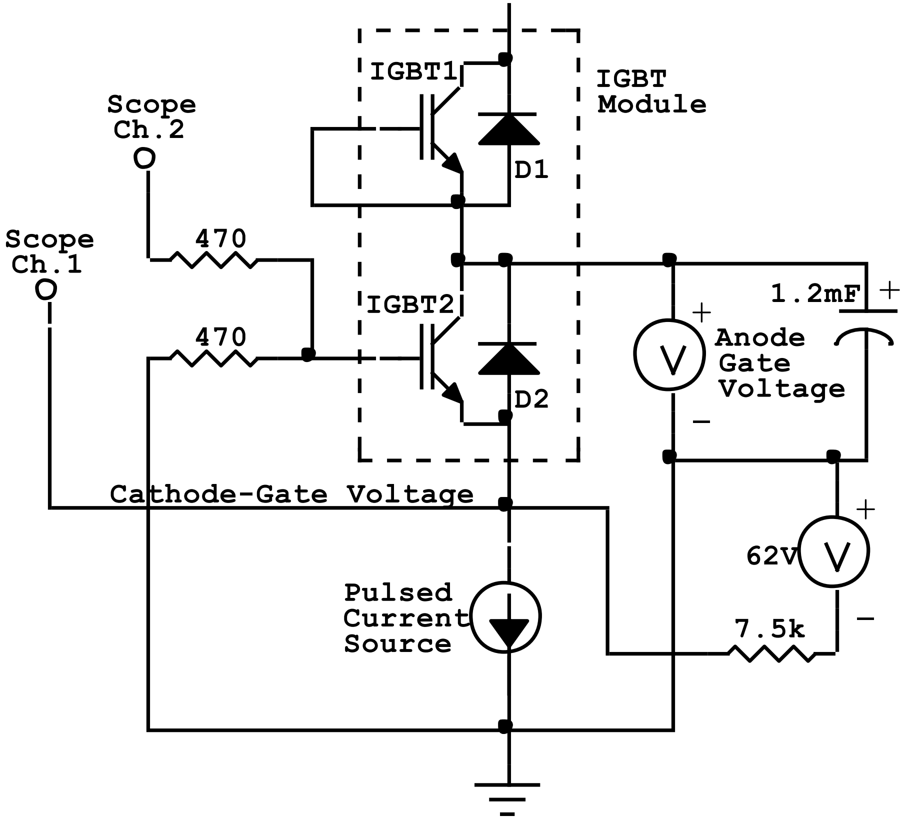
active area = 3 cm^2



*** Dashed curves based on area scaling of 10 A die to 100 A multi-chip module.**

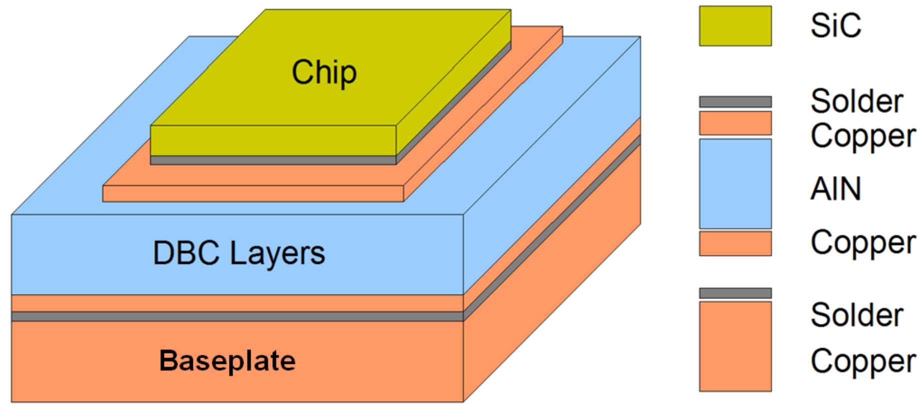
High Speed
Transient Thermal Impedance



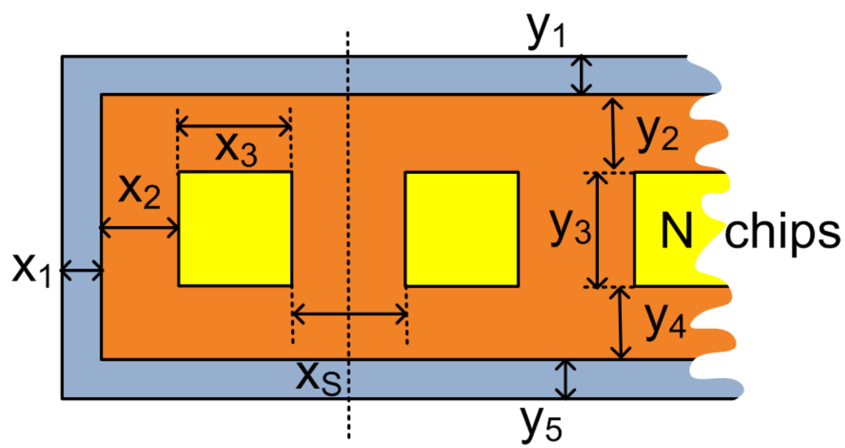


Multi-Chip Module Heat Conduction Model

Direct Bonded Cooper Voltage Isolation Stack (15 kV)



Chip and DBC Layout



Dynamic Thermal Component Model