High-Voltage Power Semiconductors - Key Enabler for Grid Transformation

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Renewables, Storage and Microgrids

Project Leader for
Power Semiconductor Devices and
Thermal Measurements

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

Grid Transformation via Power Conditioning System (PCS) Functionality

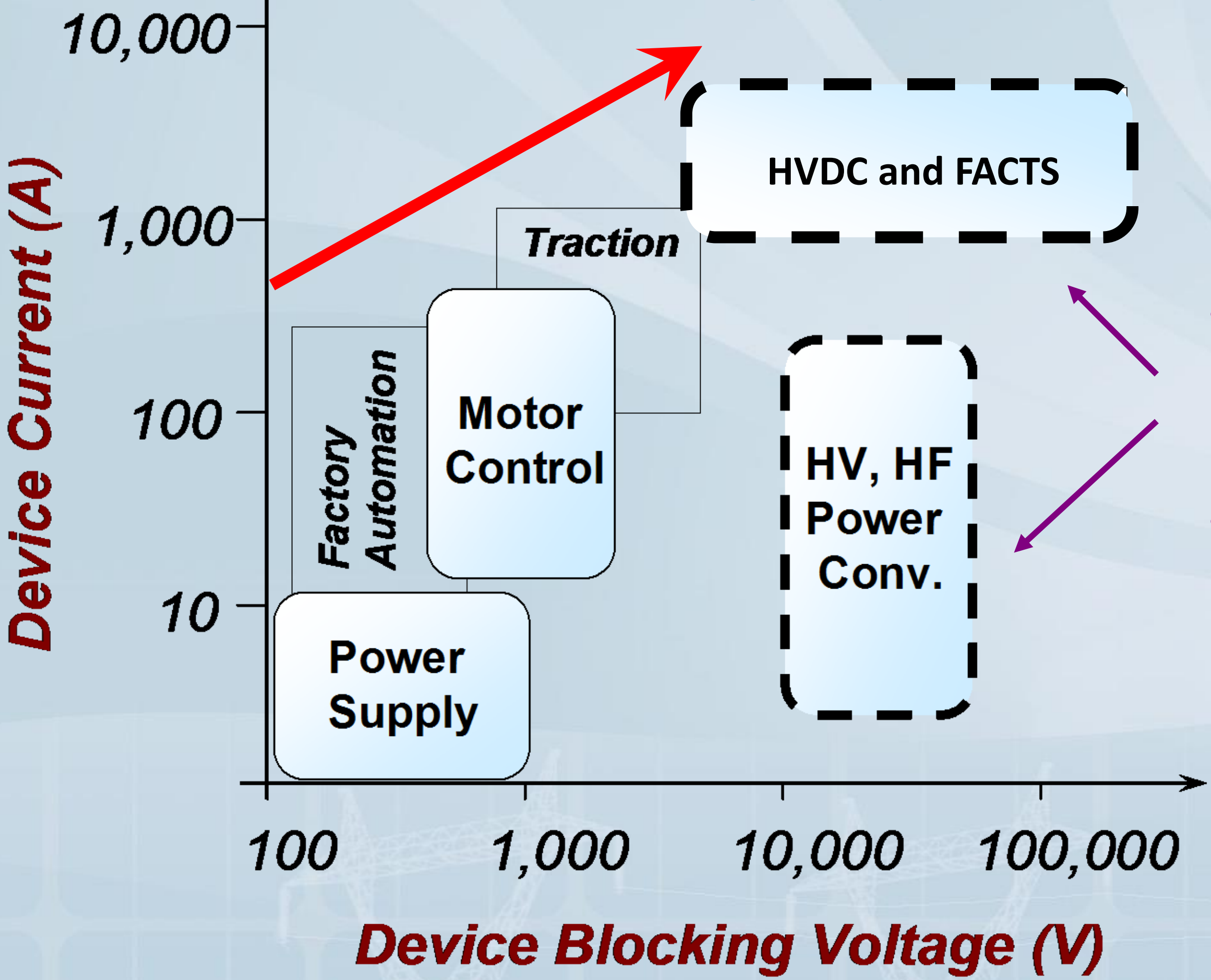
- **Today's Grid:**
  - Electricity is generated by rotating machines with large inertia
  - Not much storage: generation instantaneously matches load using
    - load shedding at large facilities
    - low efficiency fossil generators for frequency regulation
- **Future Smart Grid:**
  - High penetration 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 at low cost
- **Microgrids & automation provide secure, resilient operation**

High-Voltage, High- Frequency (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
- MV and High-Power Motors

DARPA/EPRI Megawatt Program

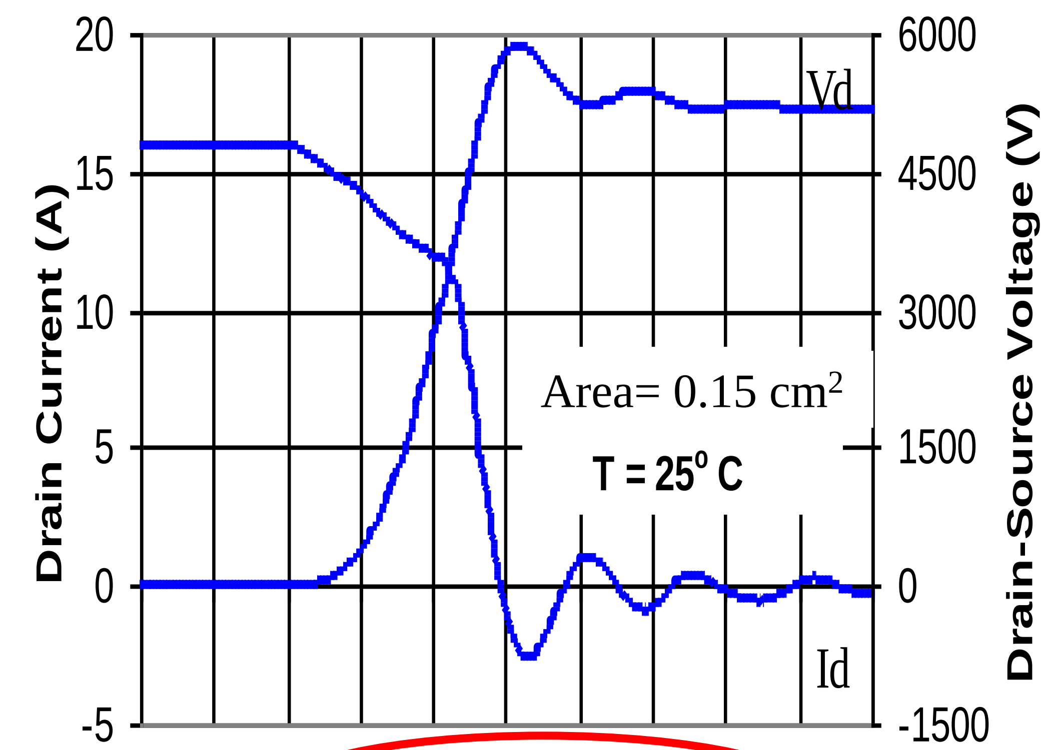
A. Hefner, et.al.; "SiC power diodes provide breakthrough performance for a wide range of applications" IEEE Transactions on Power Electronics, March 2001, Page(s):273 – 280.

DARPA/ONR/NAVSEA HPE Program

10 kV HV-HF MOSFET/JBS

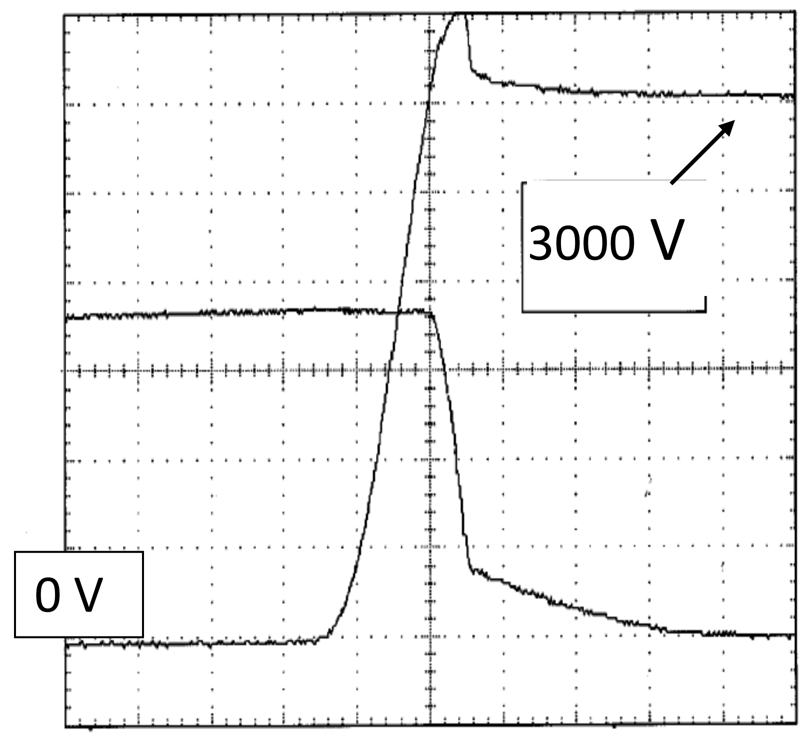
High Speed at High Voltage

SiC MOSFET: 10 kV, 30 ns



15 ns /div

Silicon IGBT: 4.5 kV, >2us

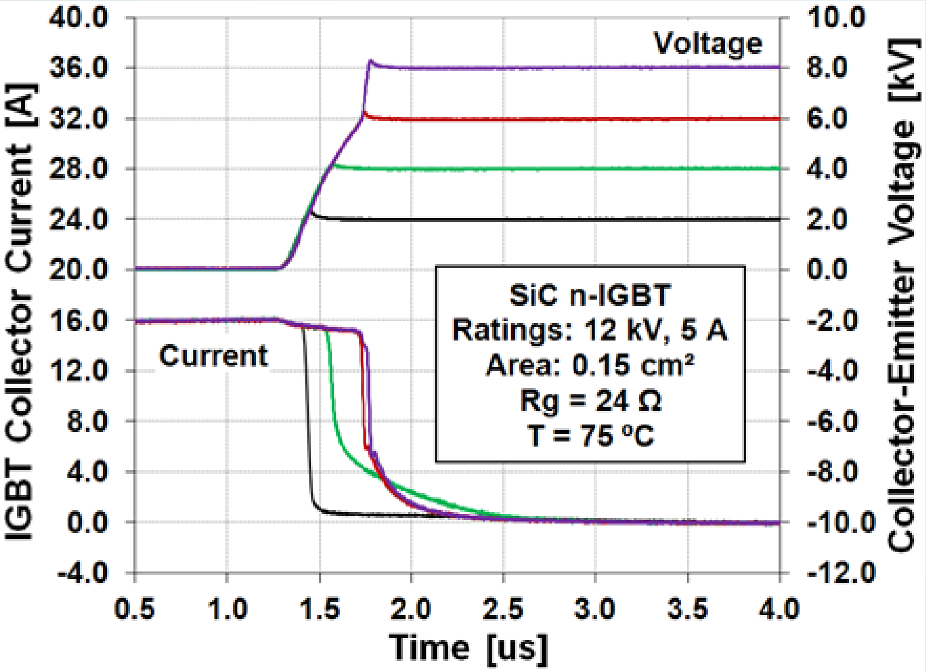


1us /div

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

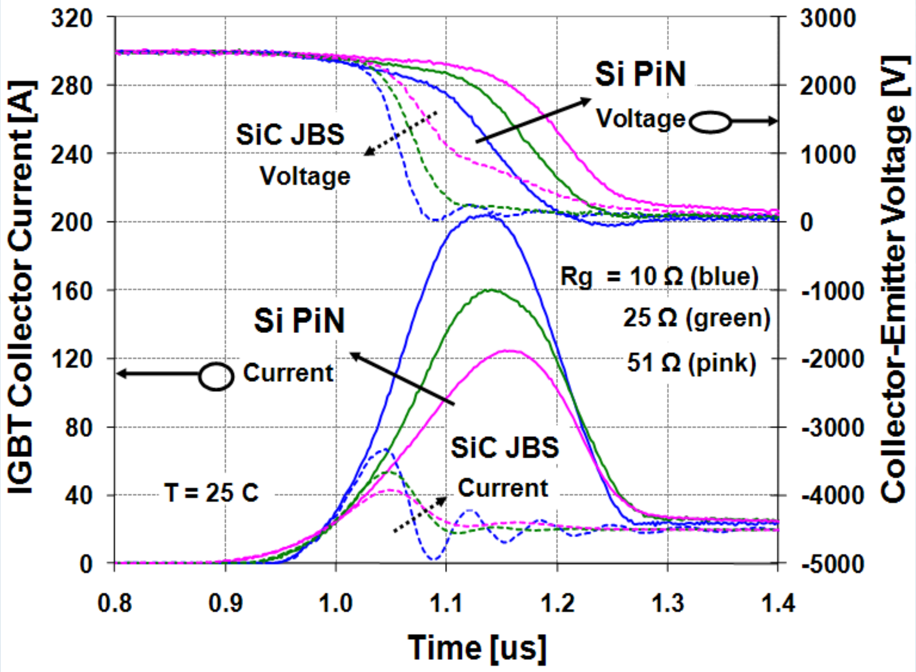
ARPA-e ADEPT
12 kV SiC IGBT
Future option

SiC IGBT: HV, high Temp, ~1 us



NRL/ONR
4.5 kV SIC-JBS/Si-IGBT
Low cost now

SiC JBS: improves Si IGBT turn-on

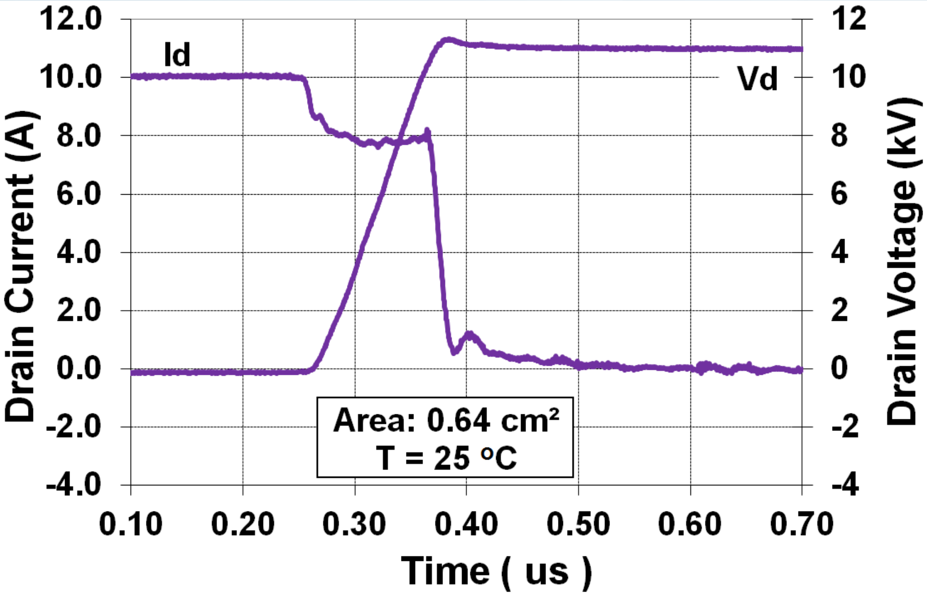


Sei-Hyung Ryu, Craig Capell, Allen Hefner, and Subhashish Bhattacharya, “High Performance, Ultra High Voltage 4H-SiC IGBTs” Proceedings of the IEEE Energy Conversion Congress and Exposition (ECCE) Conference 2012, Raleigh, NC, September 15 – 20, 2012.

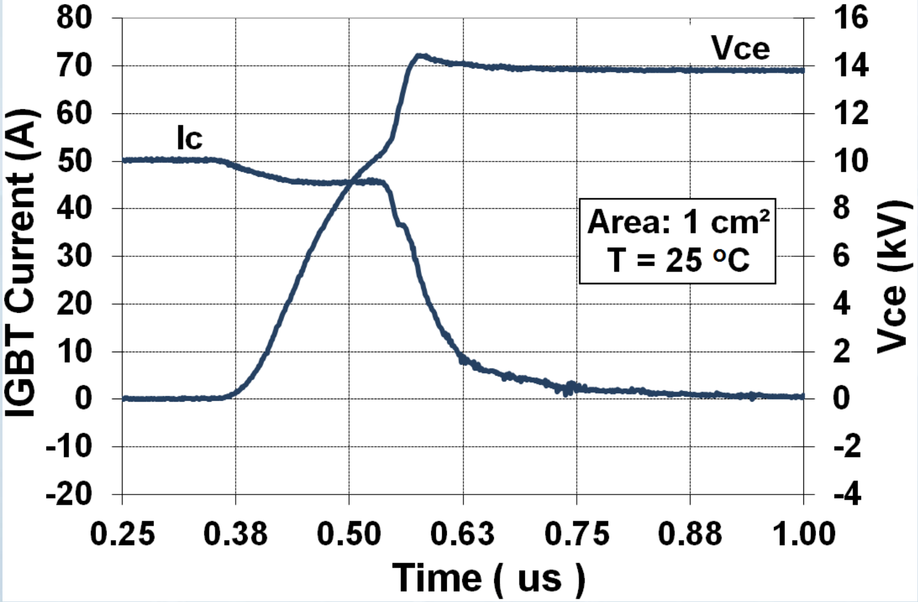
K.D. Hobart, E.A. Imhoff, T. H. Duong, A.R. Hefner “Optimization of 4.5 kV Si IGBT/SiC Diode Hybrid Module” PRiME 2012 Meeting, Honolulu, HI, October 7 - 12, 2012.

Army HVPT, Navy HEPS
SiC ManTech Program

SiC MOSFET: 15 kV, ~100ns



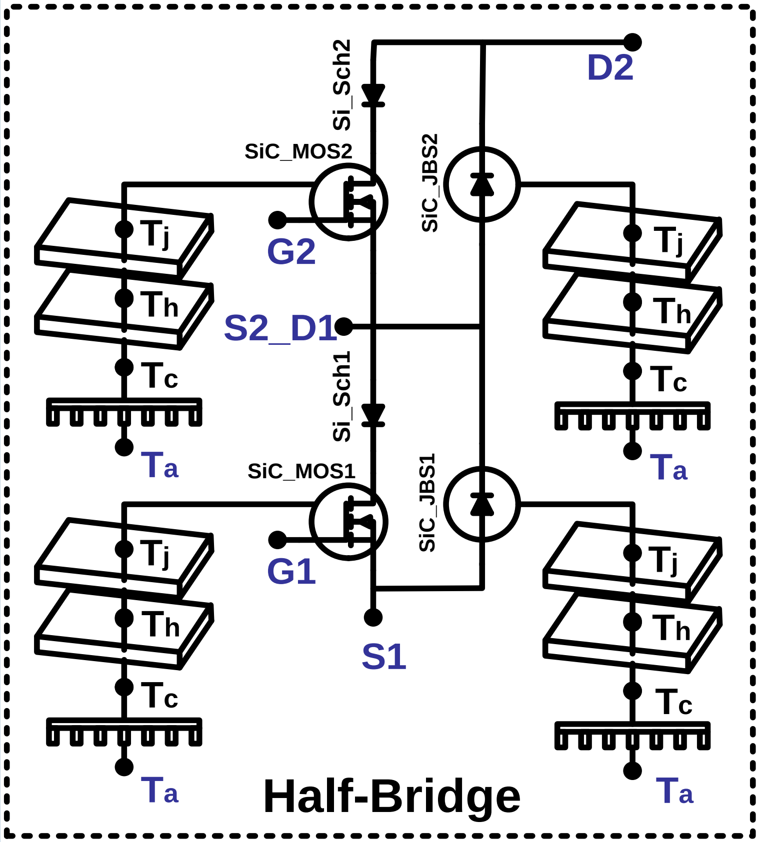
SiC n-IGBT: 20 kV, ~1us



NIST High-Megawatt PCS Workshops

- High-Megawatt Converter Workshop: January 24, 2007
- HMW PCS Industry Roadmap Workshop: April 8, 2008
- NSF Power Converters for Alternate Energy : May 15-16, 2008
- Future Large CO2 Compressors: March 30-31, 2009
- High Penetration of Electronic Generators: Dec. 11, 2009
- Plugin Vehicle Fleets as Grid Storage: June 13, 2011
- Grid Applications of Power Electronics: May 24, 2012
- High-Power Variable-Speed Motor Drives: April, 2014
- High-Power Direct-Drive Motor Systems: September, 2014

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

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

~700 V DC

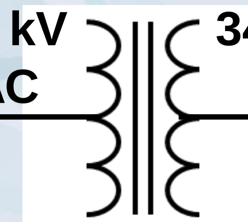
Approx. 500 Fuel Cells

•
•
•

~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



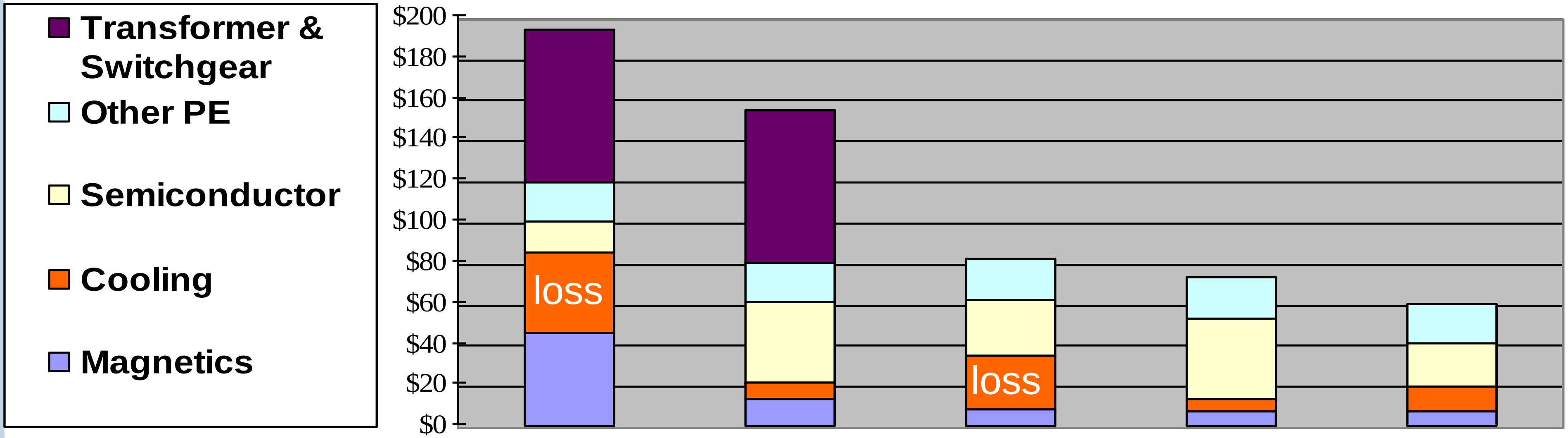
345 kV AC

$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

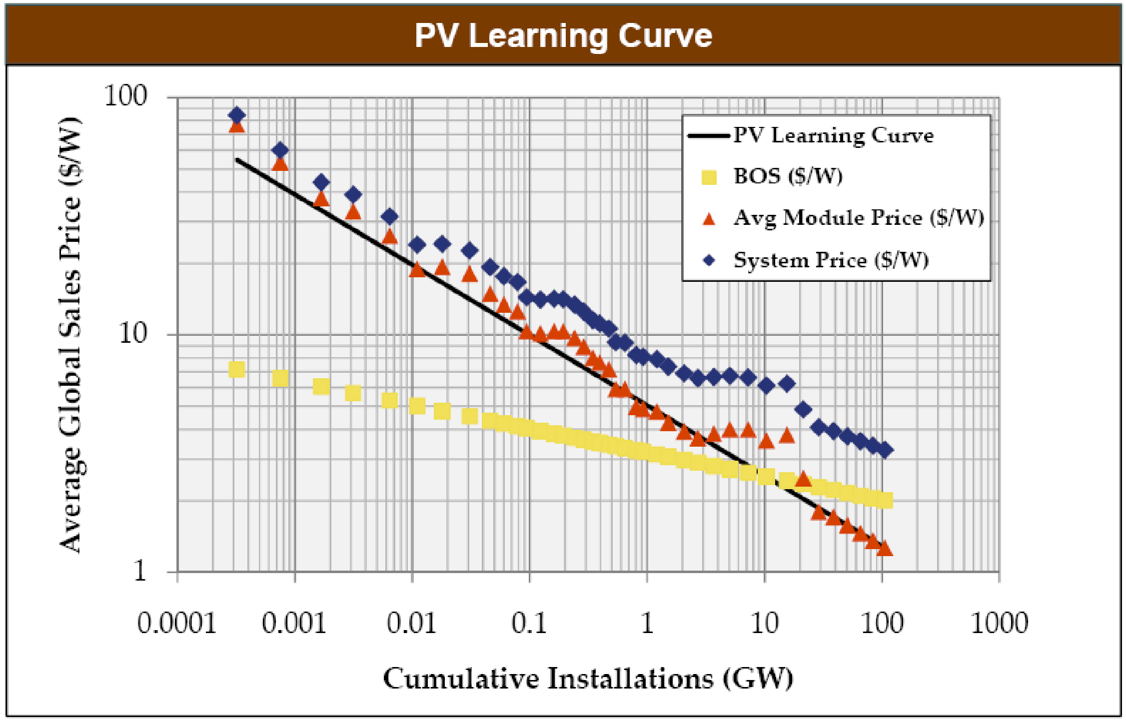
$0.4/W – BOS

$0.1/W – Power electronics

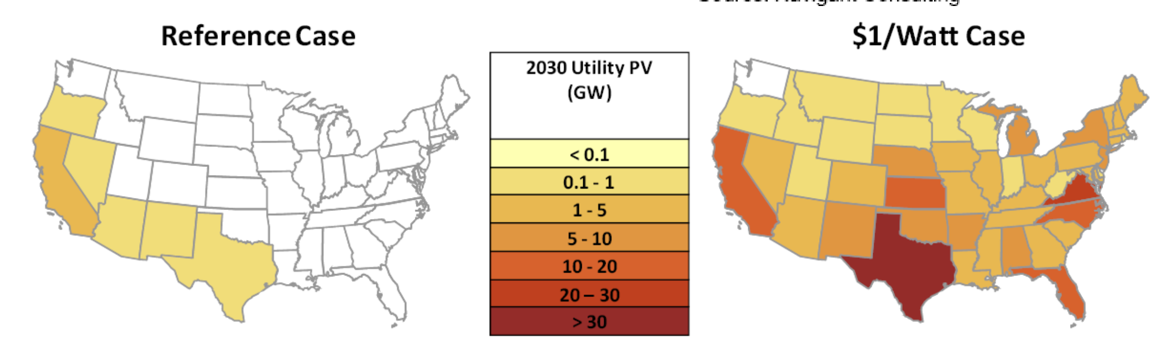
Smart Grid Functionality

High Penetration

Enhanced Grid Value



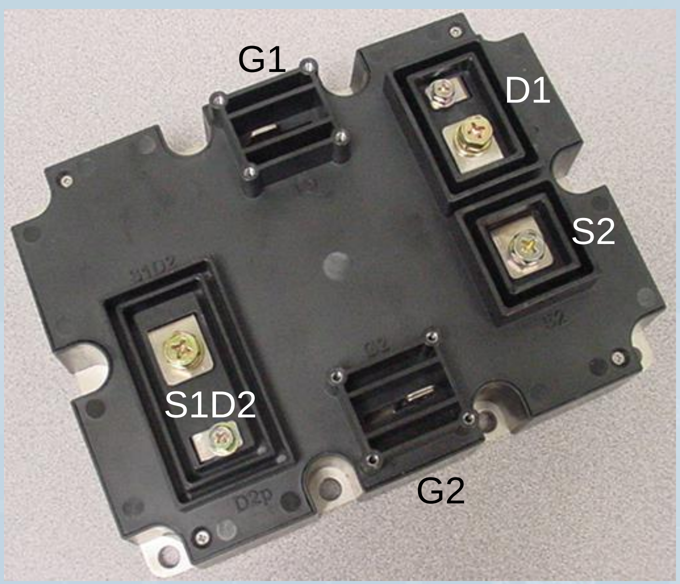
Source: Navigant Consulting

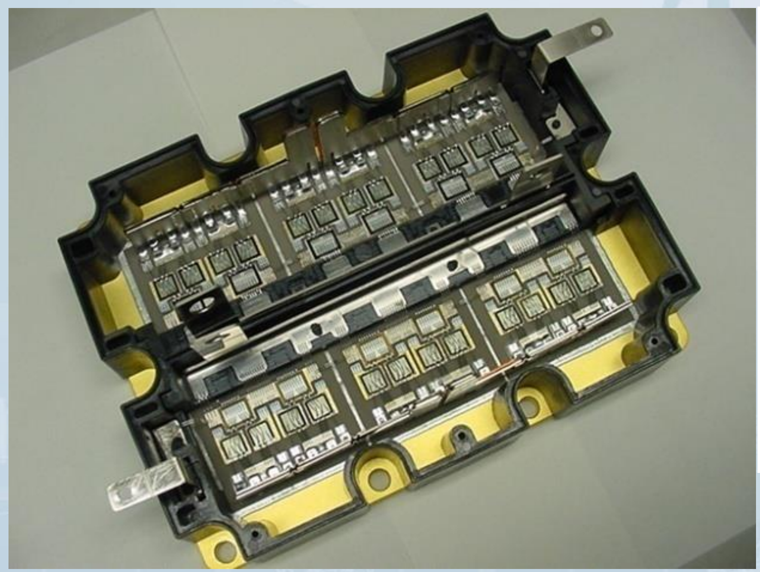


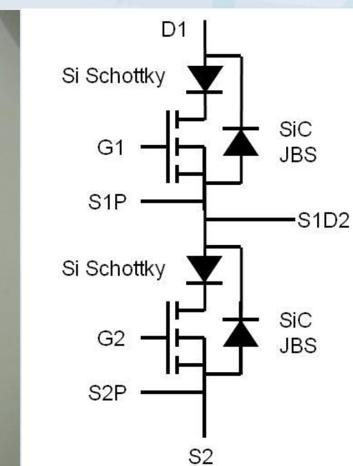
$1/W achieves cost parity in most states!

MV Direct Connect Solar Inverter (ARPA-E)

- Utilize 10kV, 120 A SiC MOSFET Module:
  - Design Developed for DARPA/ONR/NAVSEA WBG HPE Program
  - Already tested at 1 MW-scale system for HPE SSPS requirements
- MV Solar Inverter Goals:
  - Improve cost, efficiency, size, and weight
  - High speed, series connected to grid: rapidly respond/clear faults, tune power quality

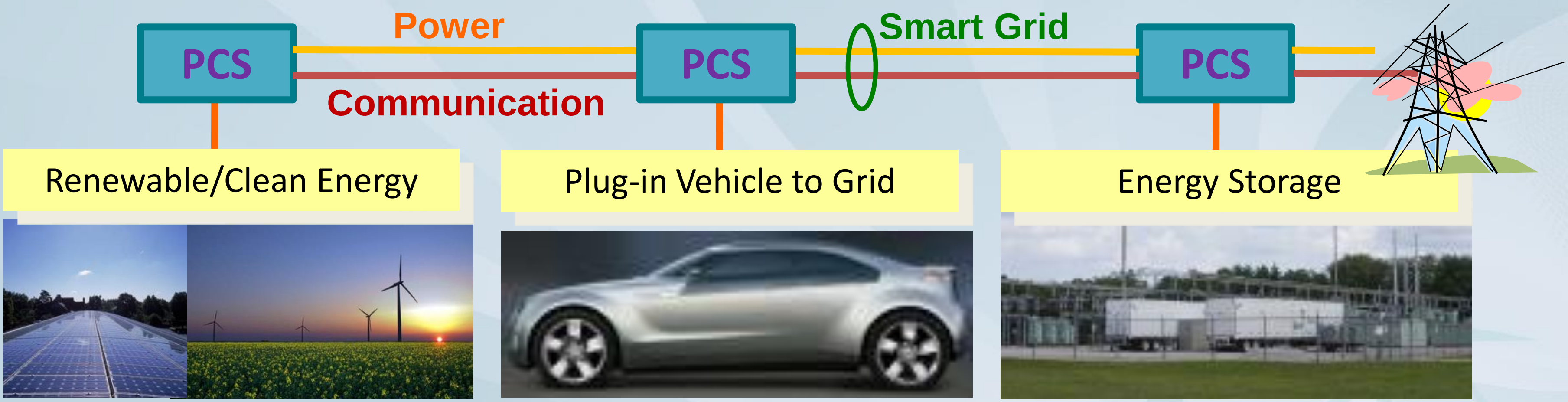






Contributed by: Leo Casey (Google)

High Penetration of Distributed Energy Resources

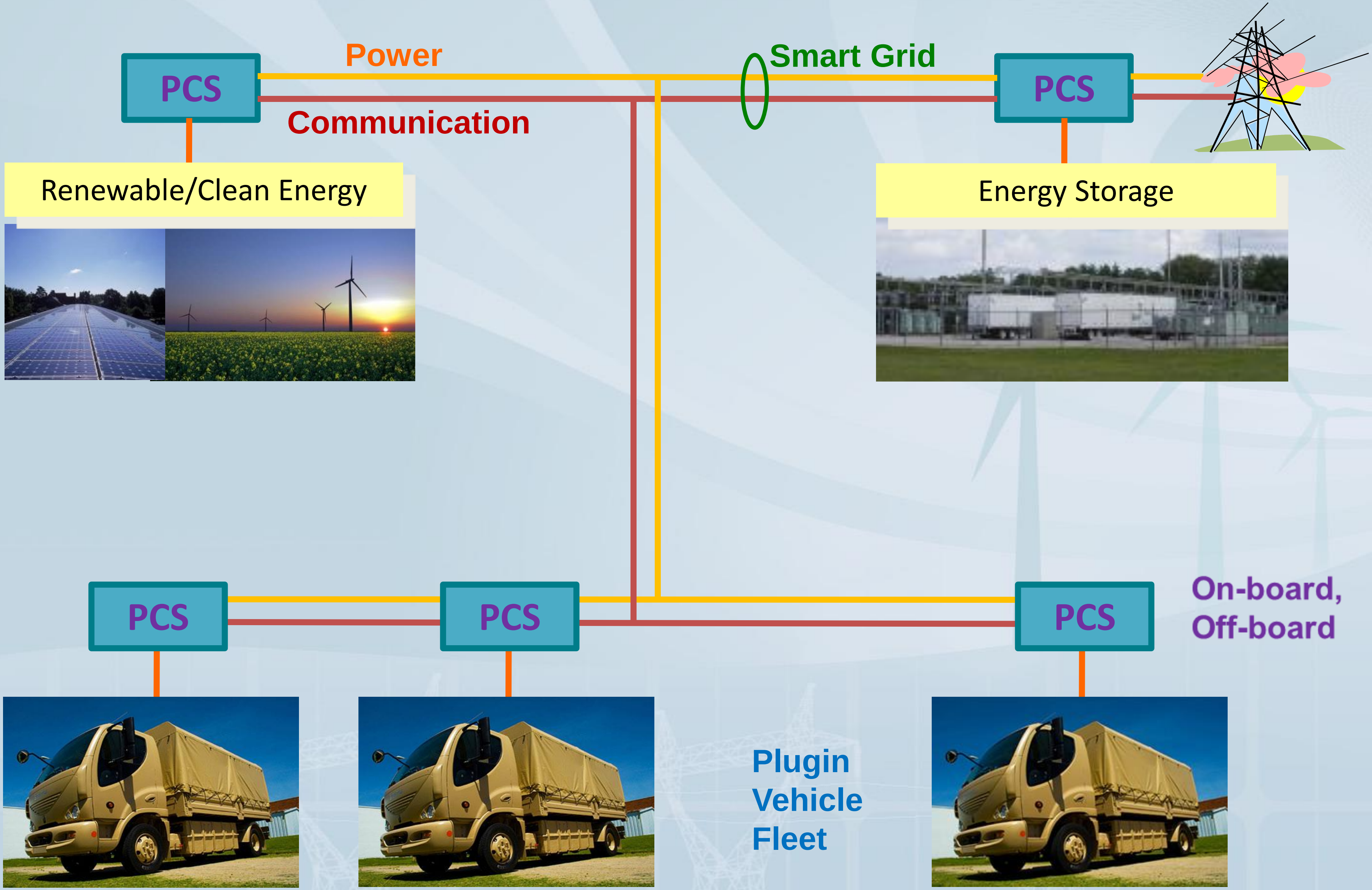


- Power Conditioning Systems (PCS) convert to/from 60 Hz AC for interconnection of renewable energy, electric storage, and PEVs

- "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 without cascading/common-mode events**
  - **Voltage regulation and utility-controlled islanding**

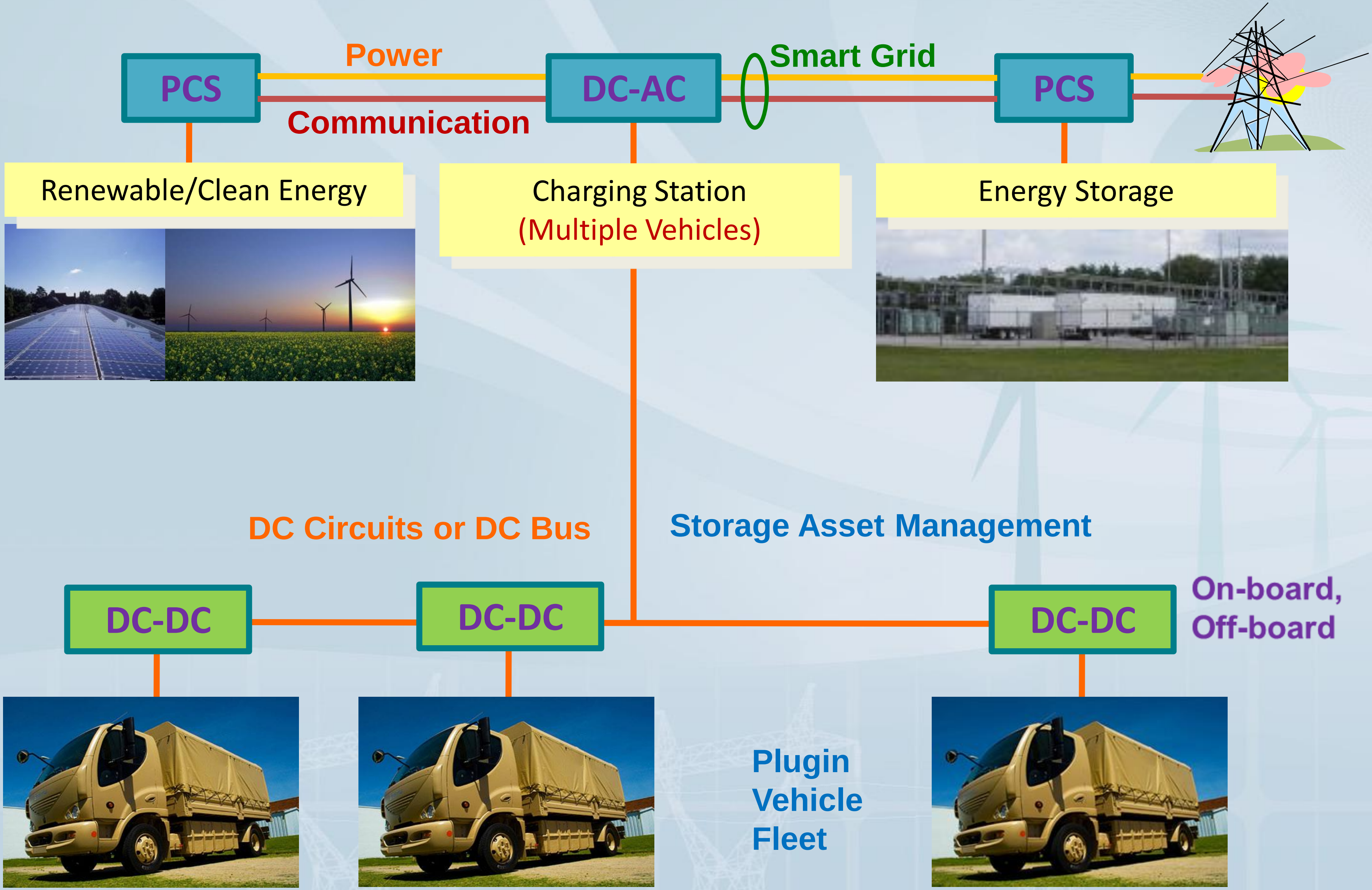
http://www.nist.gov/pml/high_megawatt/2008_workshop.cfm

PCS Architectures for PEV Fleet as Grid Storage



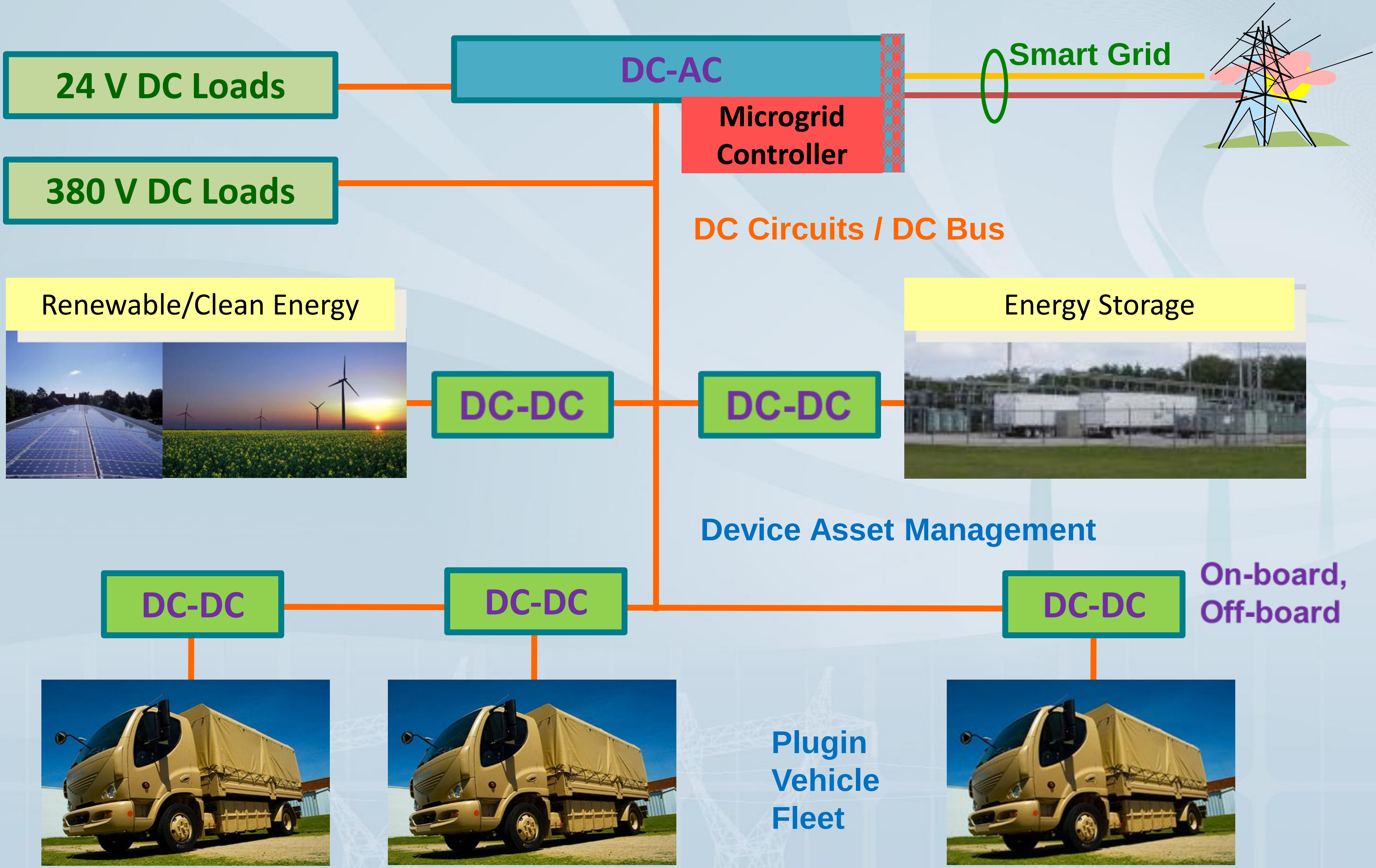
http://www.whitehouse.gov/blog/2011/09/09/air-force-jumpstarts-electric-vehicle-program

Single Large Inverter with DC Circuits to PEV Fleet

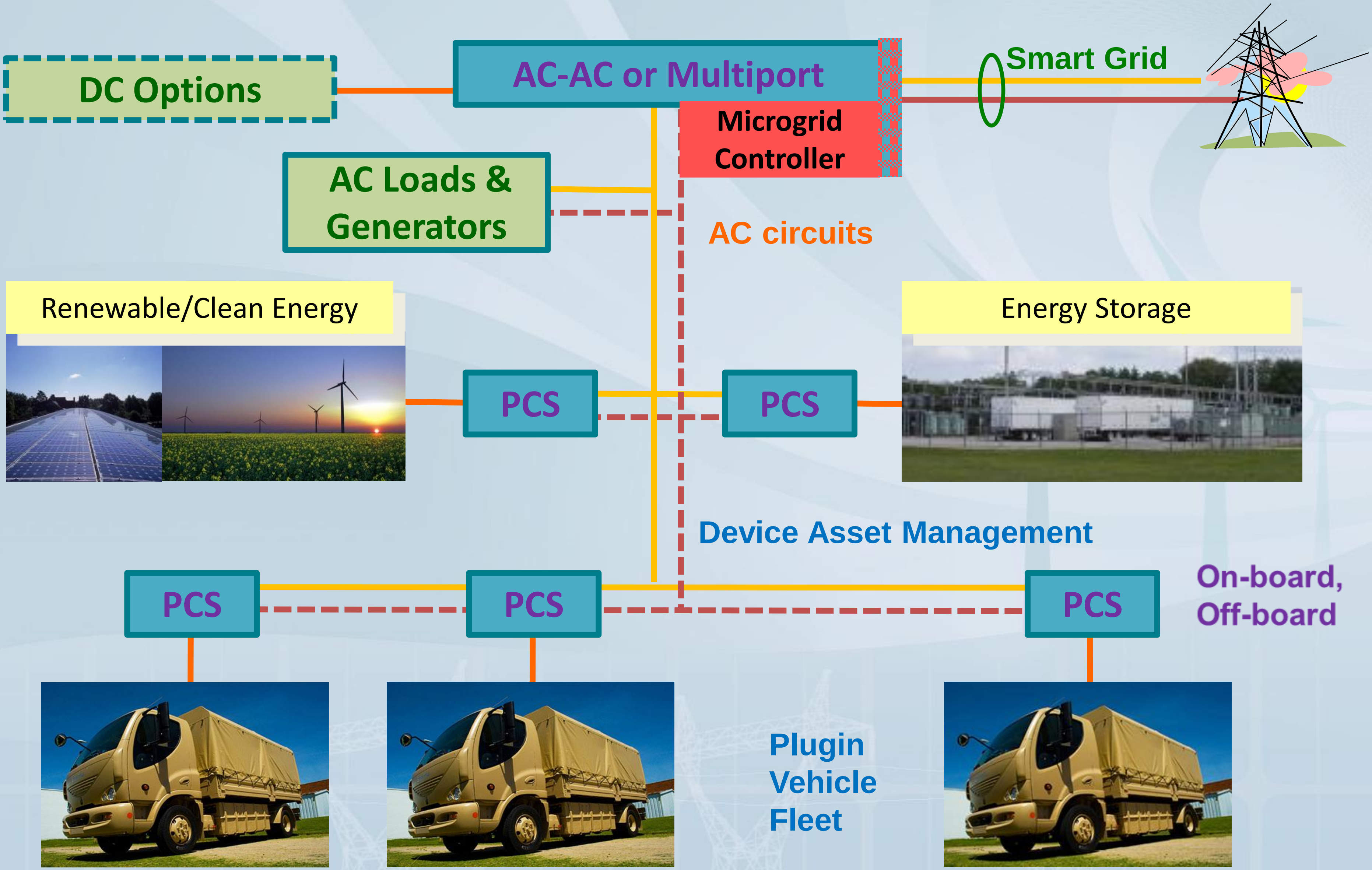


http://www.nist.gov/pml/high_megawatt/jun2011_workshop.cfm

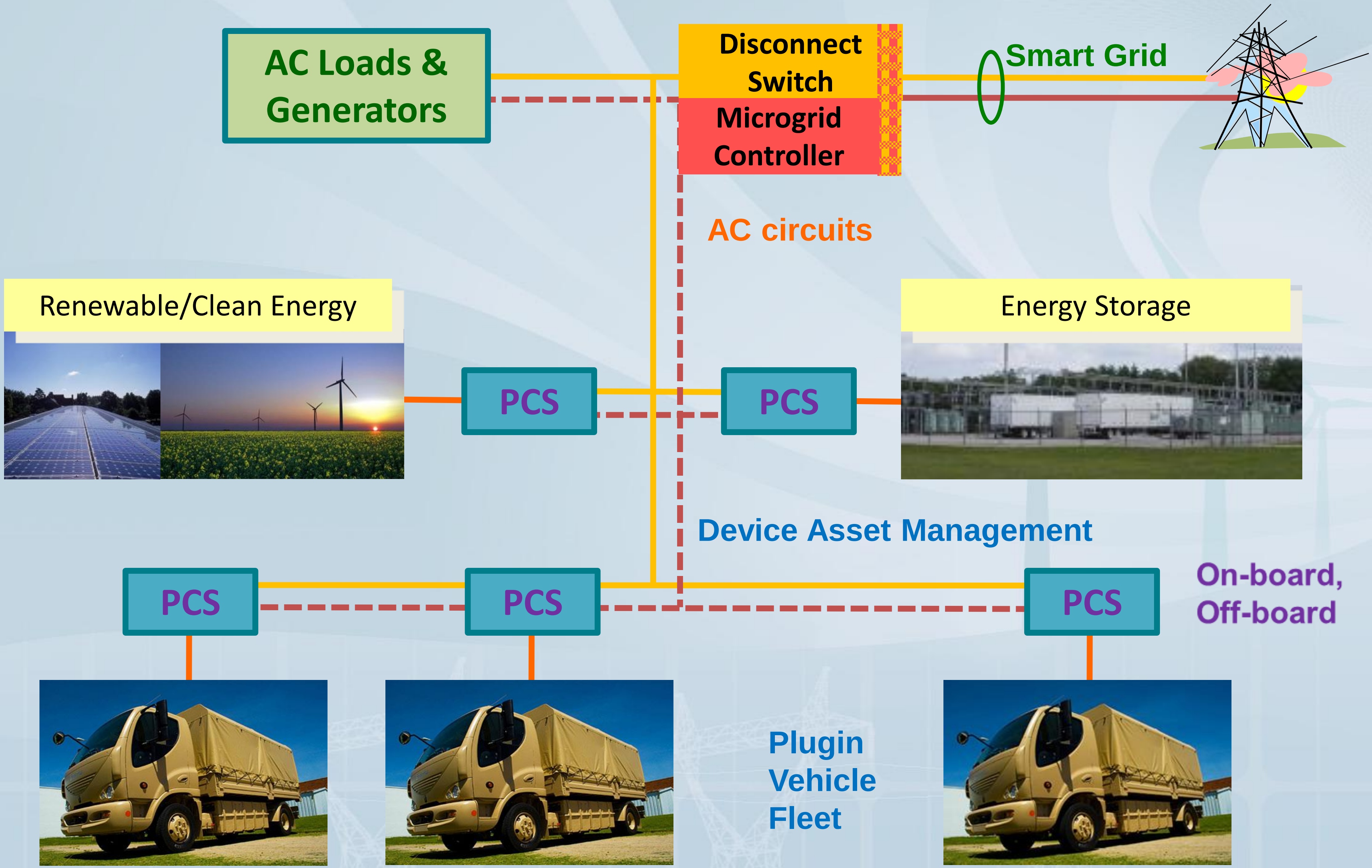
DC Microgrid: DC-AC with DC Circuits



Flow Control Microgrid: AC-AC with AC Circuits



Synchronous AC Microgrid: Disconnect and Local EMS

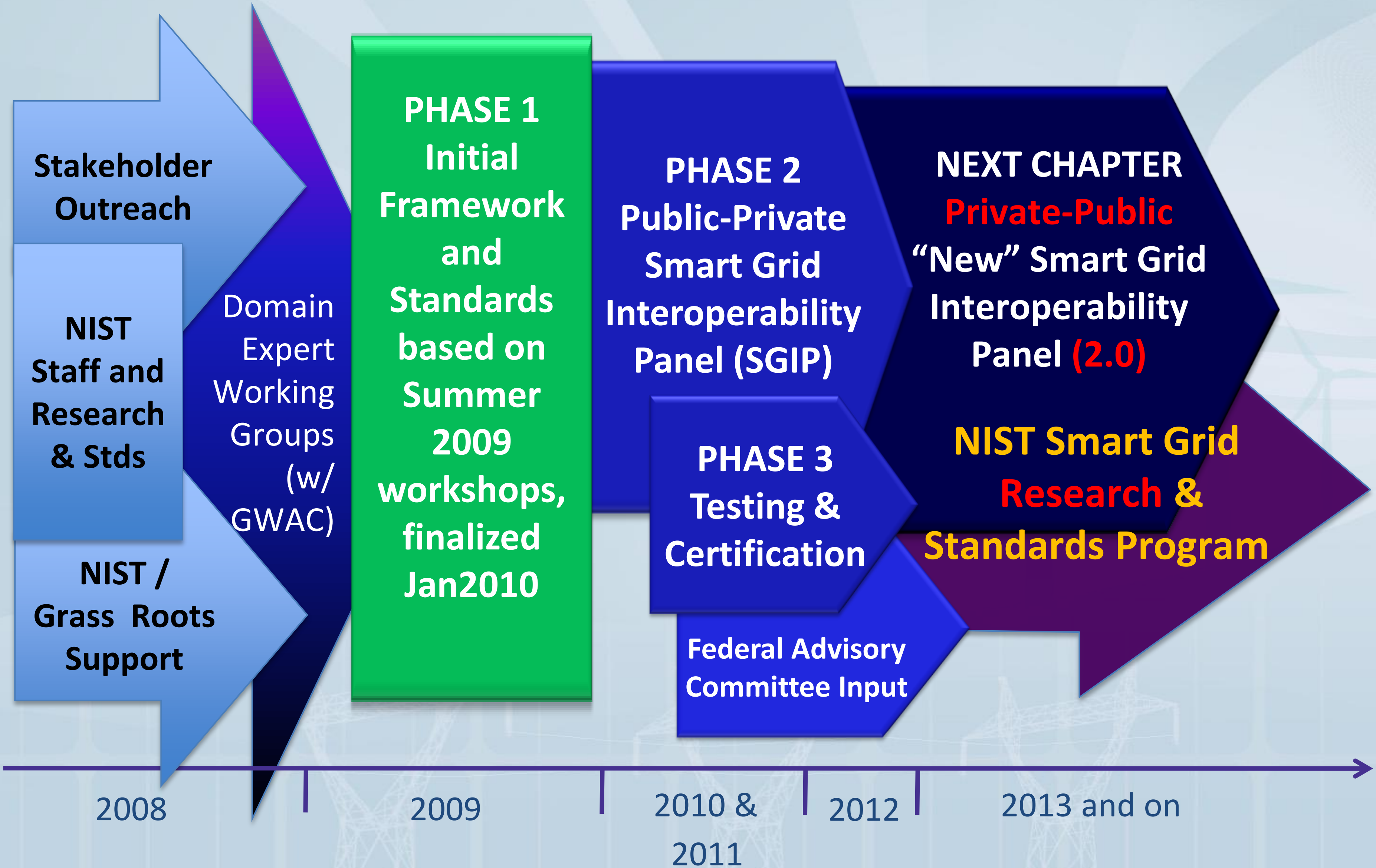


NIST Role in Smart Grid

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**…”

NIST Plan to Meet EISA'07 Responsibility



NIST Framework and Roadmap

NIST Special Publication 1108

NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0

Office of the National Coordinator for Smart Grid Interoperability

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

Release 1
January 2010

NIST Special Publication 1108R2

NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 2.0

Office of the National Coordinator for Smart Grid Interoperability,
Engineering Laboratory
in collaboration with
Physical Measurement Laboratory
and
Information Technology Laboratory

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

Release 2
February 2012

Release 3
Summer 2014

- **Public Comment closed May**
- **www.nist.gov/smartgrid**
- **New topic "Resiliency"**

NIST Special Publication 1108R3

NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0

Smart Grid and Cyber-Physical Systems Program Office
and Energy and Environment Division,
Engineering Laboratory

in collaboration with
Physical Measurement Laboratory
and
Information Technology Laboratory

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

NIST Smart Grid Interoperability Testbed

SGIP Smart Grid Interoperability

NIST Measurement Science

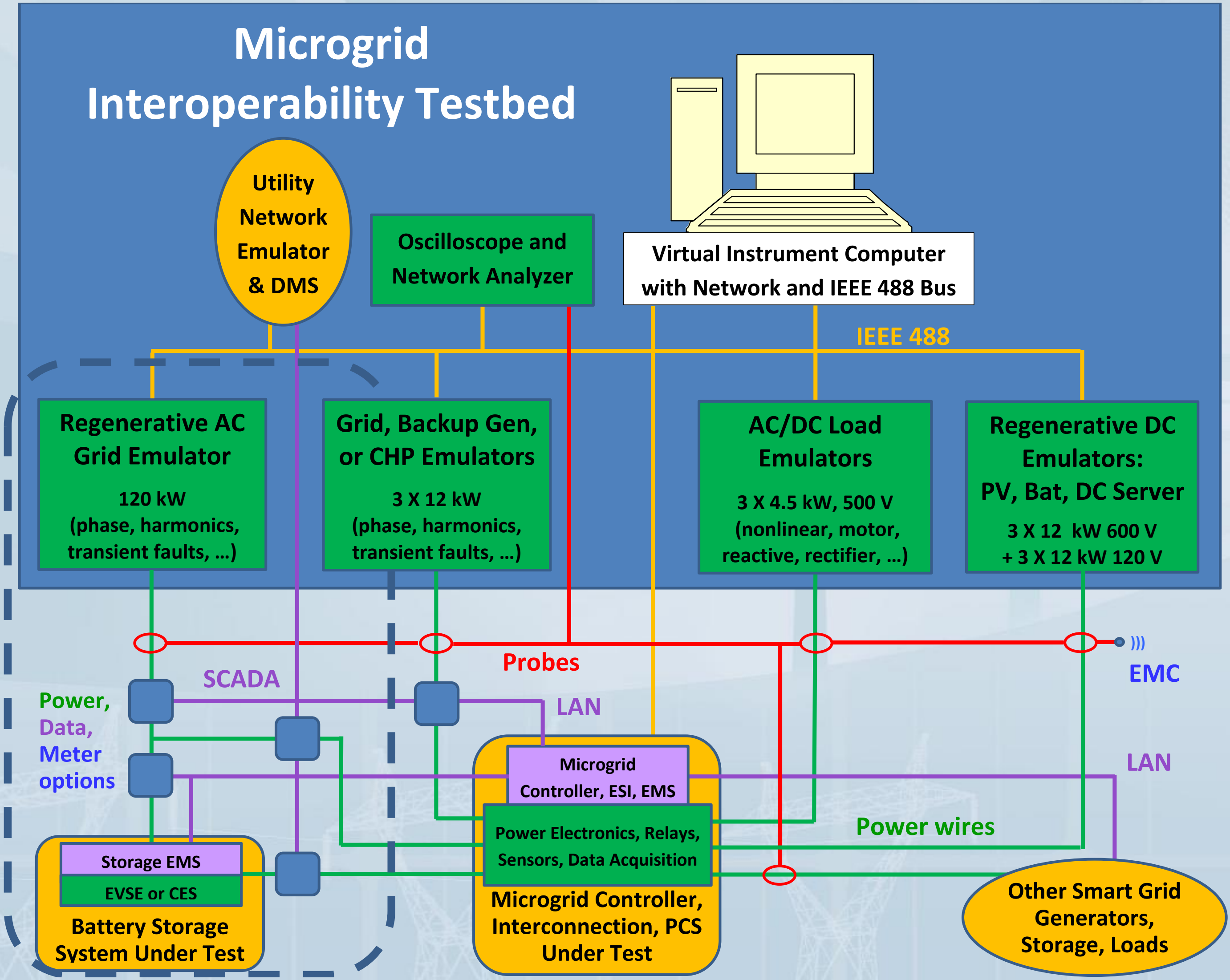
DOE/DOD Labs, Test & Certification

ESI, EMS, Microgrid & Storage functions

IT Networks, Cyber Security, EMC, Sensors & Smart Meters

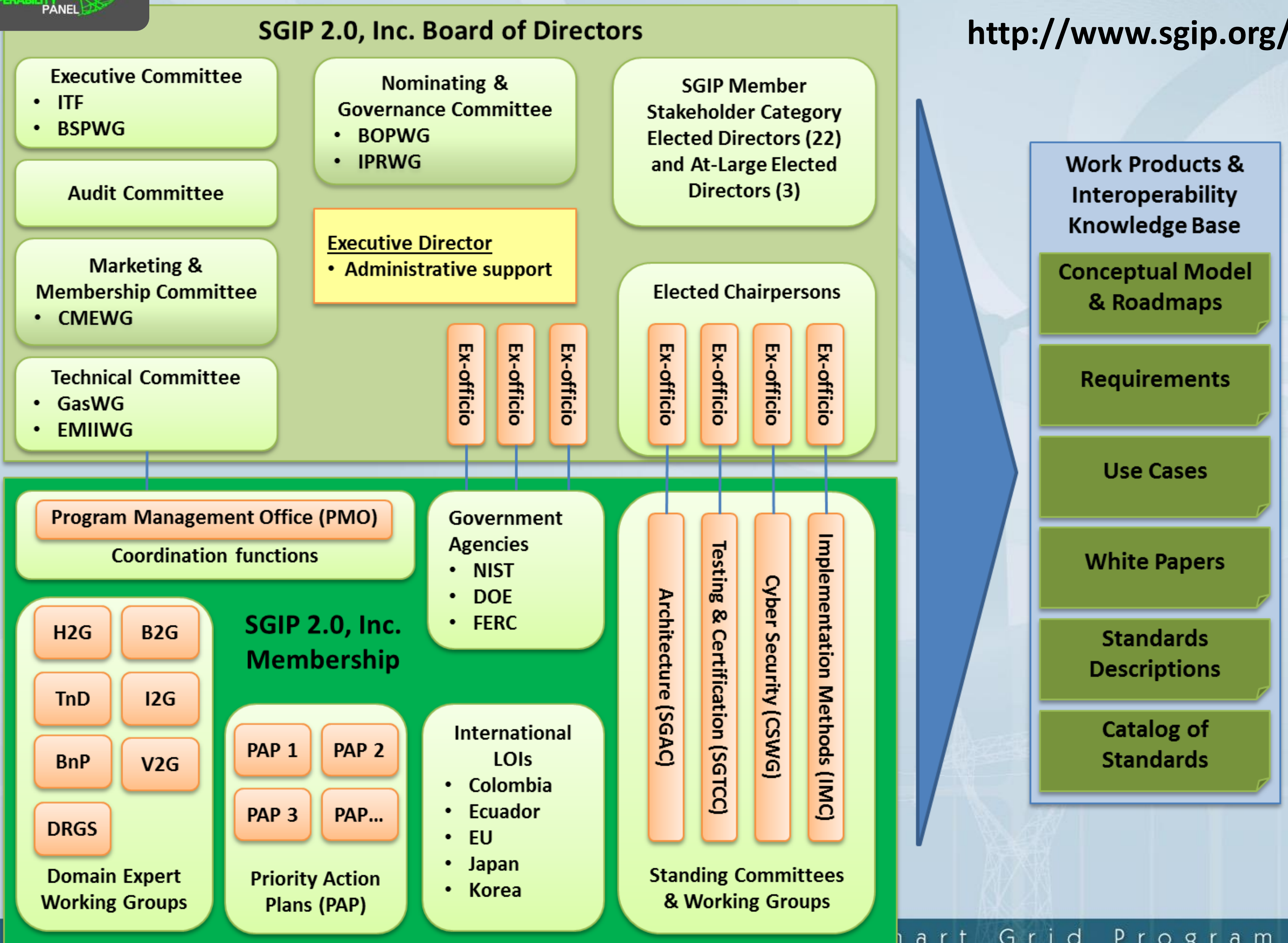
Power Electronic Interconnection Equipment

Grid-Interactive Microgrid, DER & Smart Appliances



SGIP 2.0 Inc, Organization (Draft)

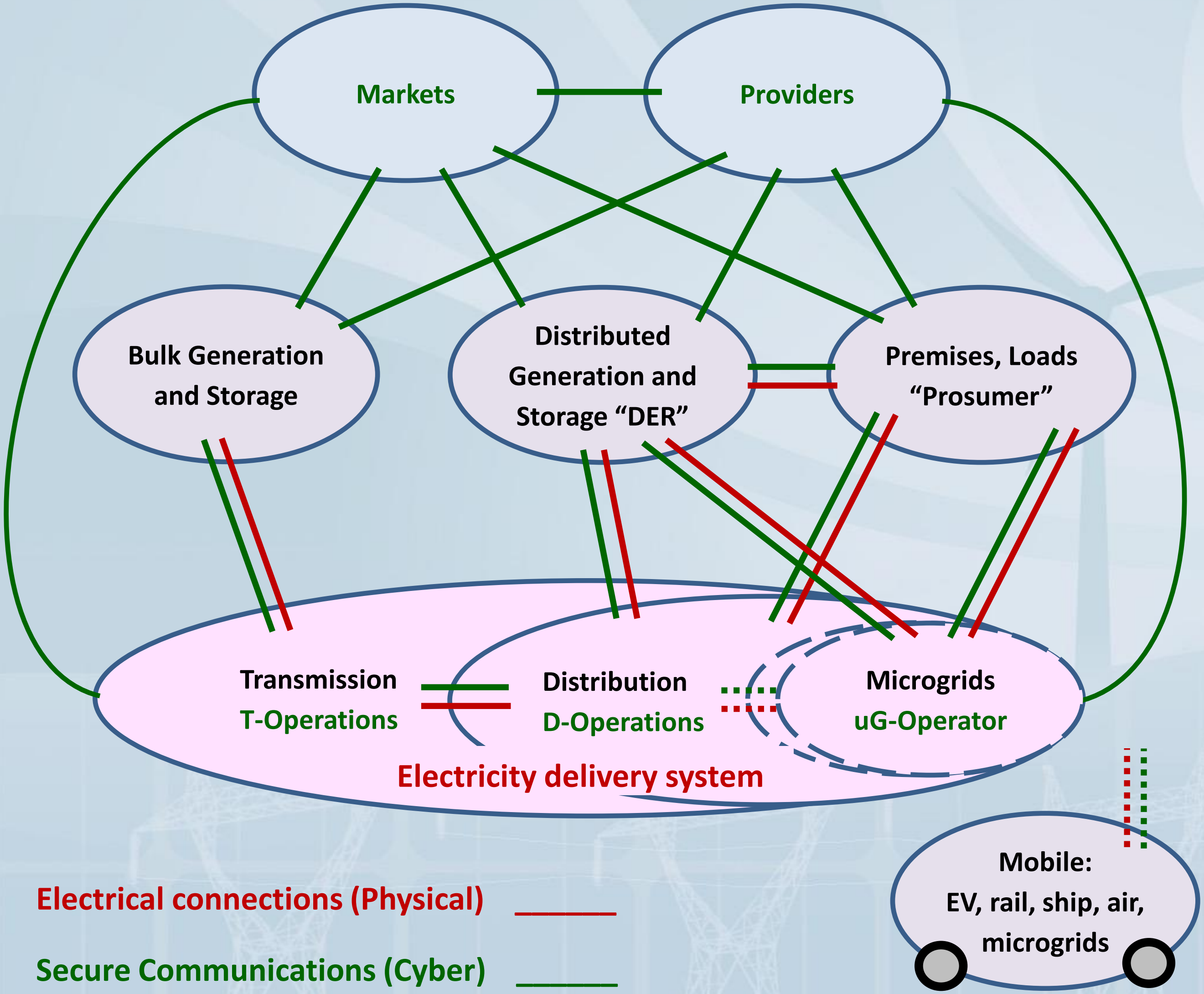
http://www.sgip.org/



Distributed Renewables, Generators and Storage DEWG

- **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-**Roadmap, **B-**Information, **C-**Microgrid,
  D-Test, **E-**Regulatory, **F-**Interconnection

Cyber-Physical Architecture for Resilient/Transactive Electricity Delivery Systems



PAP 7: Smart Grid ES-DER Standards

Task 0: Scoping Document

Prioritized timeline for ES-DER standards

Task 1: Use Cases, *EPRI Smart Inverter

Define requirements for different scenarios

Task 2: IEEE 1547.4 for island applications and IEEE 1547.6 for secondary networks

Task 3: Unified interconnection method with multifunctional operational interface for range of storage and generation/storage.

IEEE 1547.8

(a) Operational interface
(b) Storage without gen
(c) PV with storage
(d) Wind with storage
(e) PEV as storage

Info exchanges

MIC

PAPs

Task 4: DER Object Models and Mappings

IEC 61850-7-420, -90-7: Expanded to include

- Multifunctional ES-DER operational interface
- Harmonized with CIM & MultiSpeak
- Map to MMS, DNP3, web services, & SEP 2

Task 5: Test, Safe and Reliable Implementation

UL 1741, NEC-NFPA70, SAE, CSA and IEC

PAP 24: Microgrid Operational Interfaces