Workshop on High-Megawatt Direct-Drive Motors and Front-End Power Electronics

Al Hefner (NIST)

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

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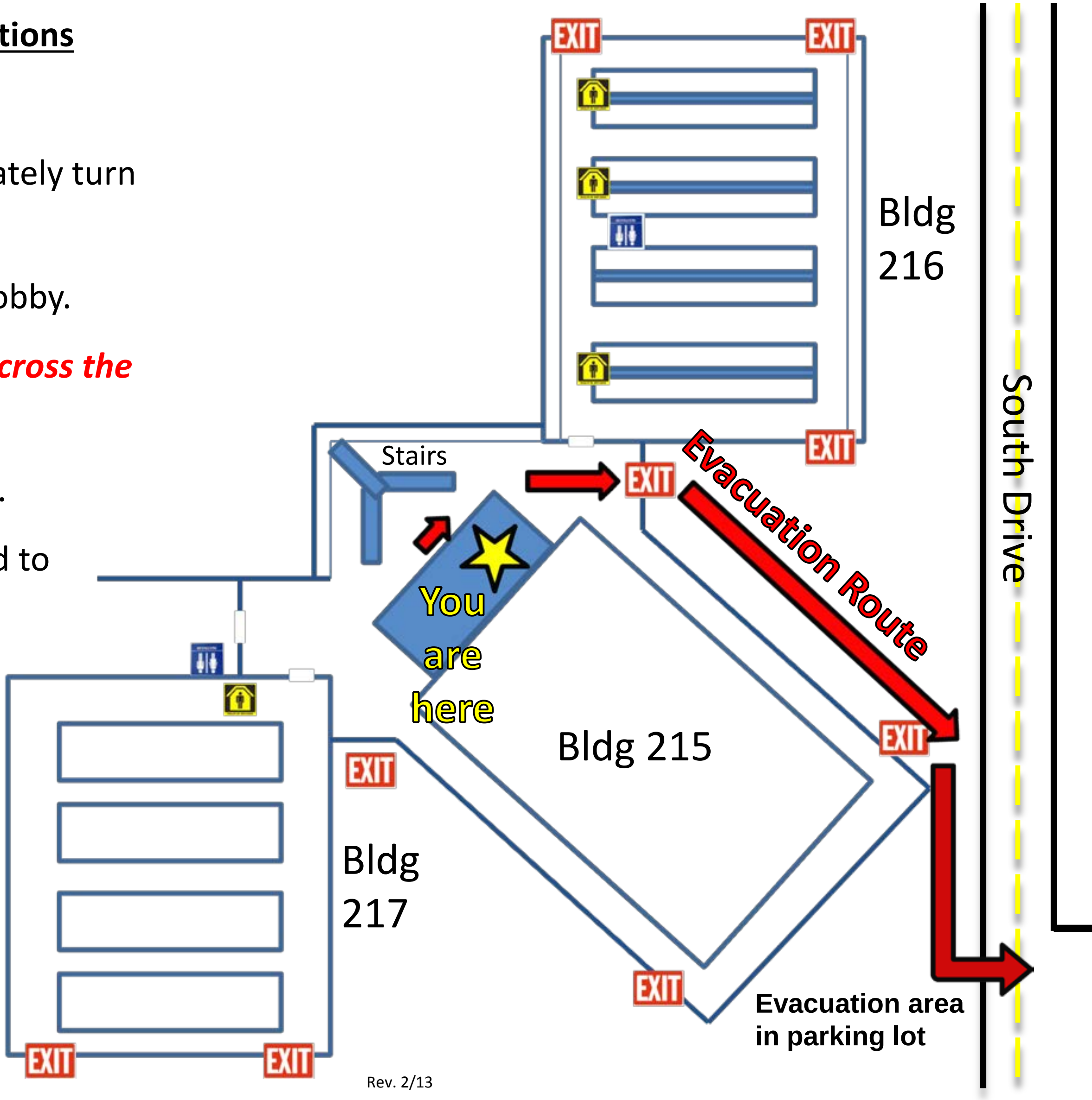


Organizers

Al Hefner (NIST)

Anant Agarwal (DOE AMO)

Leo Casey (Google)

Ravi Raju (GE Global Research)

Tom Lipo (Consultant)

Waqas Arshad (ABB)

Ron Wolk (Consultant)

Ridah Sabouni (Energetics)

Colleen Hood (NIST)

Tam Duong (NIST)

Jose Ortiz (NIST)

John Reichl (Northrop Grumman)

AGENDA – Morning

8:30am Introduction Session (Al Hefner):

Participant Introductions **(name, affiliation, HMW VSD interest)**

Previous HMW Workshops & Workshop Goals and Key Questions **– Al Hefner**

DOE EERE Needs for Program Planning **– Anant Agarwal**

ABB – Applications of High-RPM DD Motors in COG Industries (NG, LNG) **– Waqas Arshad**

GE OG – Applications for High-Speed Motors in Oil and Gas Industries **– Ravi Raju**

10-10:30am Break

Panel: Integration of Mechanical and Drive Technology for High-Speed Motors (Tom Lipo):

ABB/Baldor – Motor mechanical/drive system integration **– Steve Englebretson**

UTK – Benefits of high-speed SiC drives for integrated direct-drive motor system **– Leon Tolbert**
– Fred Wang

GE Electrical Machines – Integration of SiC power devices into high-power motor drives
– Ayman EL-Refaie

Teco Westinghouse – High-Speed direct-drive motors enabled by SiC power devices
– Paulo Guedes-Pinto

Lunch 12- 1pm

Panel discussion (30 min)

AGENDA – Afternoon

1:30pm **Panel: WBG Devices Cost and Development Roadmap (Leo Casey):**

Cree – Power products roadmap plans for commercialization of SiC power switches and power diodes from 2012-2020 **– Jeff Casady**

Cree – Power products reliability data and pricing forecasts for power module, power MOSFET and power diode products from 650V to 15kV **– John Palmour**

United SiC – Economic viability of SiC power commercial foundry approach **– Anup Bhalla**

Monolith – Foundry process integration and product roadmap and cost projections for 1200V/1700V devices **– Sujit Banerjee**

APEI – Manufacturing low cost SiC module packages **– Kraig Olejniczak**

3-3:30pm Break

Panel discussion (30min)

4pm **Panel: Advanced motor and drive technology (Ravi Raju):**

PNNL – Magnetic Materials for Motors **– Jun Cui**

NCSU – High-voltage, high-frequency SiC power electronics **– Subhashish Bhattacharya**

Panel discussion (15 min)

5pm Adjournment

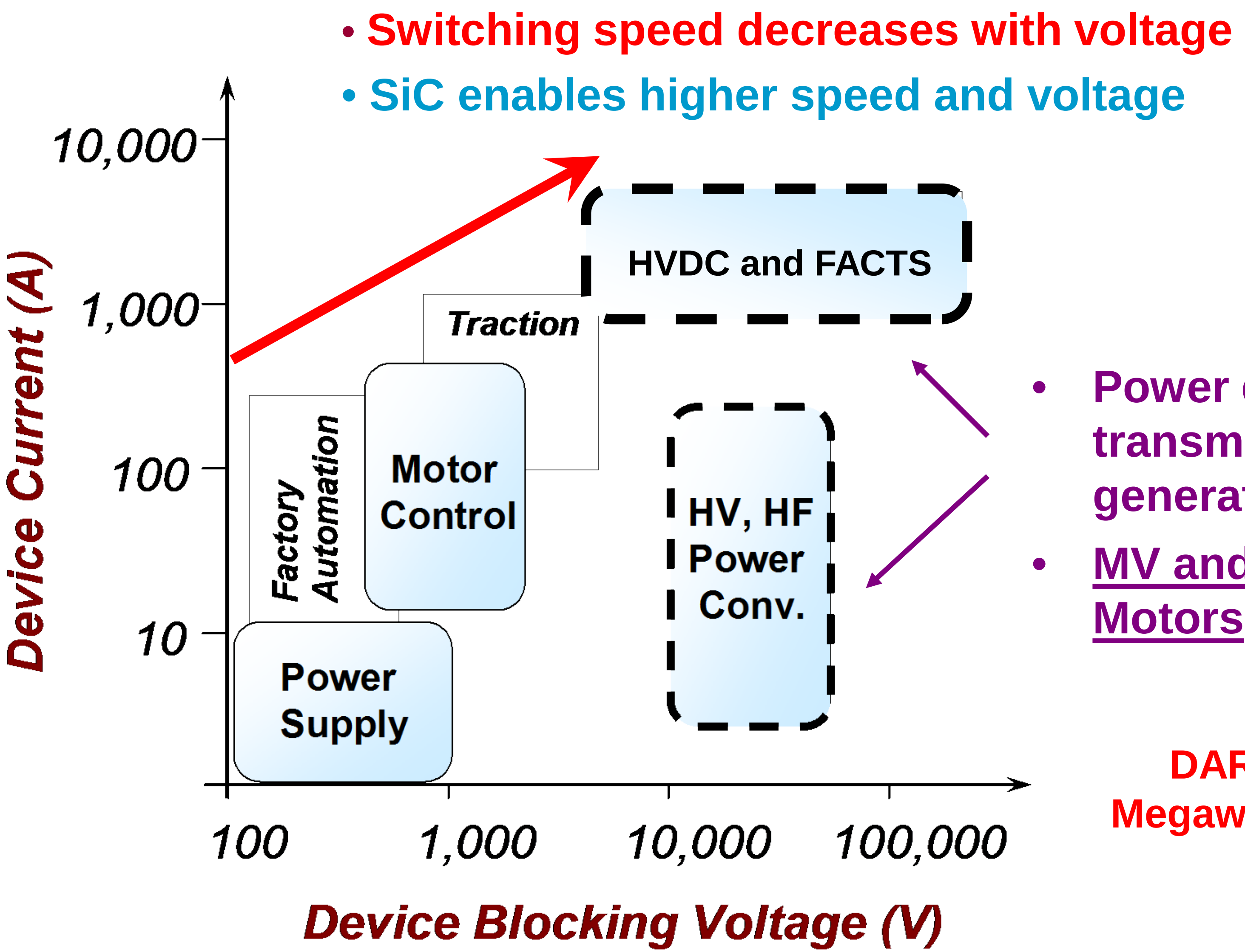
NIST High-Megawatt PCS Workshops

- **High-Megawatt Converter Workshop: January 24, 2007**
  - Begin to identify technologies requiring development to meet PCS cost and performance goals for the DOE SECA
- **HMW PCS Industry Roadmap Workshop: April 8, 2008**
  - Initiate roadmap process to offer guidance for further development of high-megawatt converters technology
- **National Science Foundation (NSF): May 15-16, 2008**
  - Establish power electronics curriculums and fundamental research programs for alternate energy power converters
- **Future Large CO2 Compressors: March 30-31, 2009**
  - Prioritize R&D gaps for future CO2 compression systems at large central Coal and Natural Gas plants
- **High Penetration of Electronic Generators: Dec. 11, 2009**
  - High-MW electronics required to achieve the goals of high penetration of renewable/clean energy systems
- **Plugin Vehicle as Grid Storage: June 13, 2011**
  - PCS Architectures for Plugin-Vehicle Fleets as Grid Storage
- **Grid Applications of Power Electronics: May 24, 2012**
- **MV and High-Power Variable-Speed Motor Drives: April, 2014**

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



- Power distribution, transmission and generation
- MV and High-Power Motors

DARPA/EPRI Megawatt Program

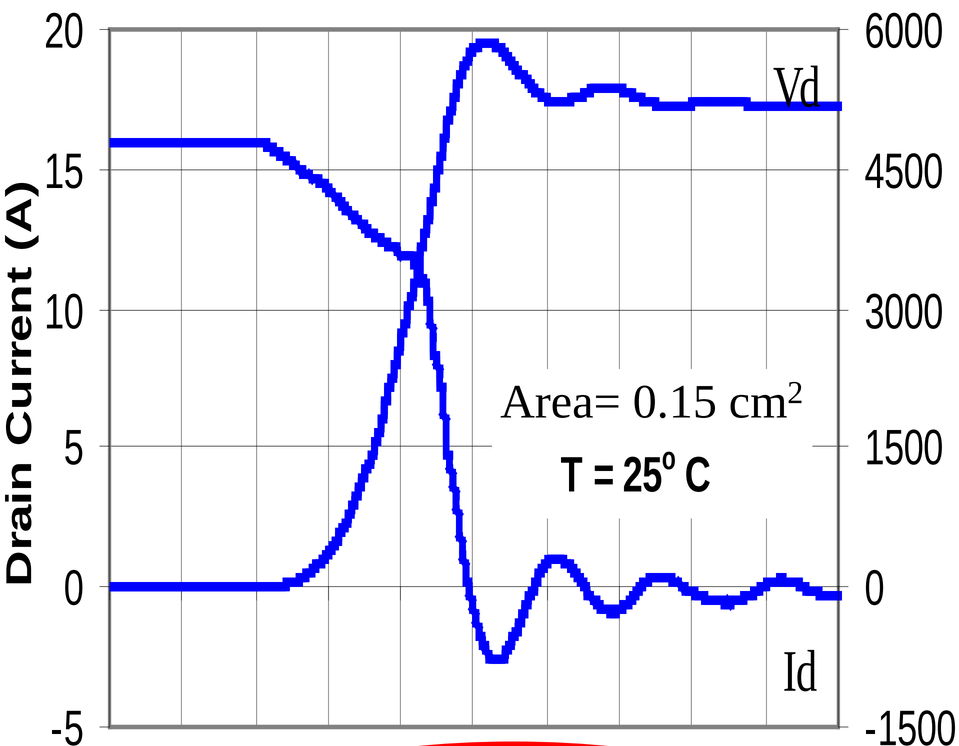
A. Hefner, et.al.; "SiC power diodes provide breakthrough performance for a wide range of applications" IEEE Transactions on Power Electronics, March 2001, Page(s):273 – 280.

DARPA/ONR/NAVSEA HPE Program

10 kV HV-HF MOSFET/JBS

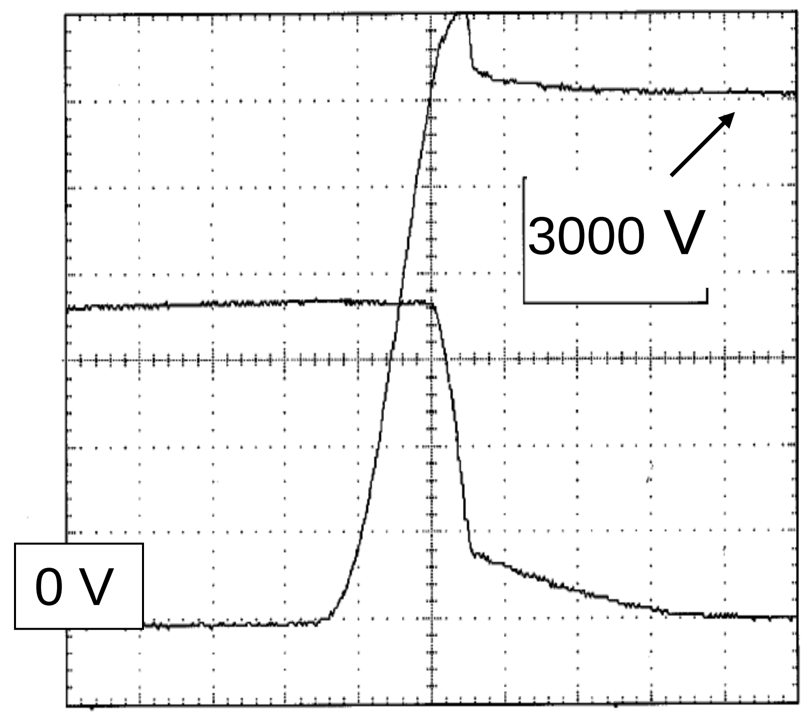
High Speed at High Voltage

SiC MOSFET: 10 kV, 30 ns



15 ns /div

Silicon IGBT: 4.5 kV, >2us



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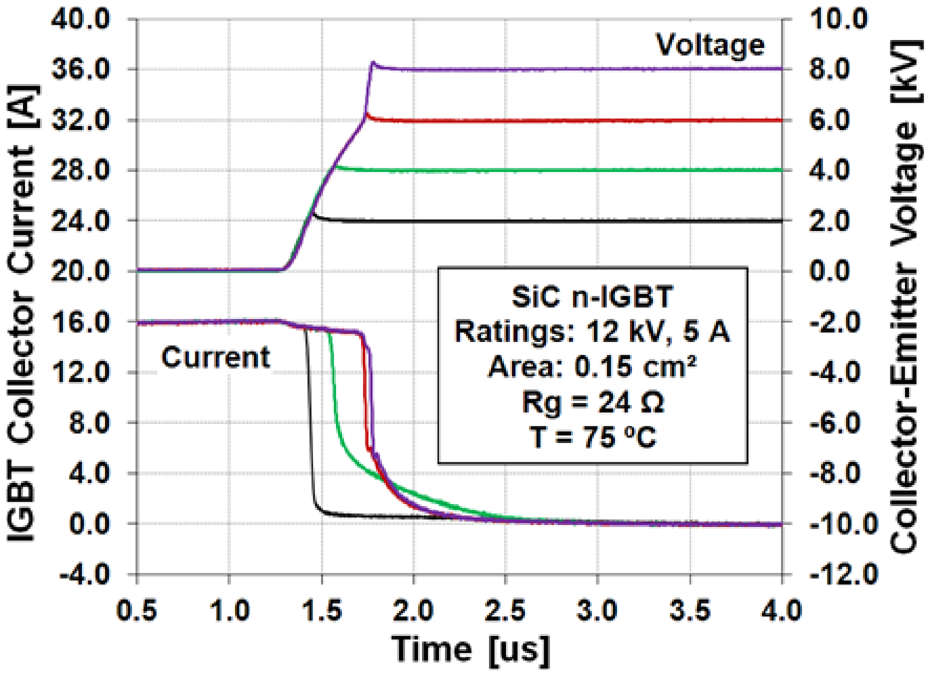
A. Hefner, et.al. “Recent Advances in High-Voltage, High-Frequency Silicon-Carbide Power Devices,” *IEEE IAS Annual Meeting,* October 2006, pp. 330-337.

ARPA-e ADEPT

12 kV SiC IGBT

Future option

SiC IGBT: HV, high Temp, ~1 us

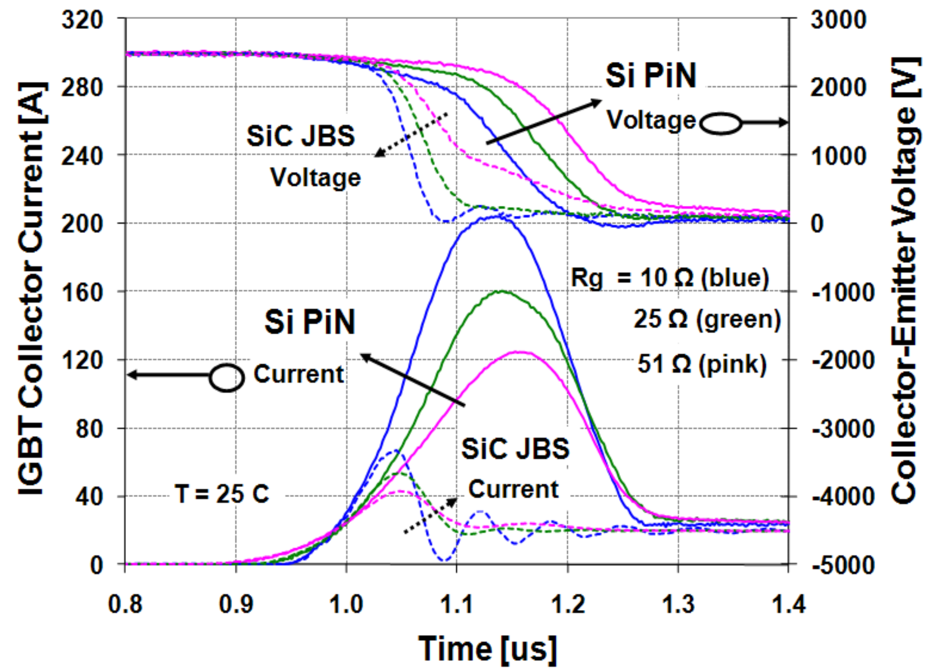


NRL/ONR

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

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SiC n-IGBT: 20 kV, ~1us

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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/

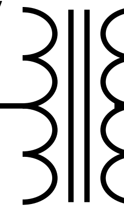
~700 V DC

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



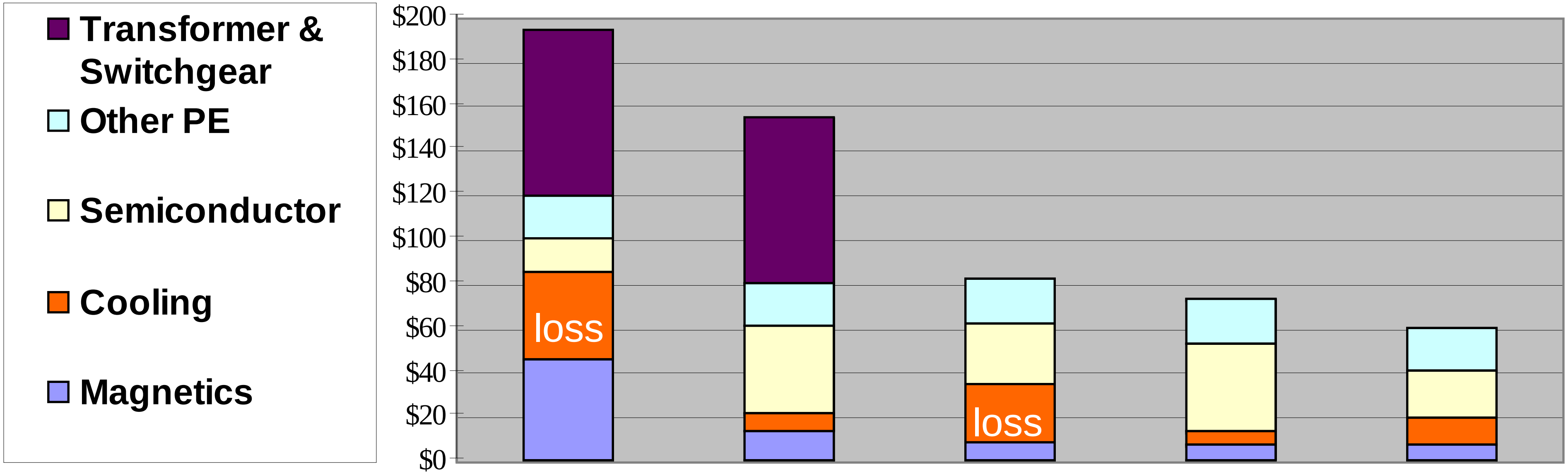
345 kV AC

$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

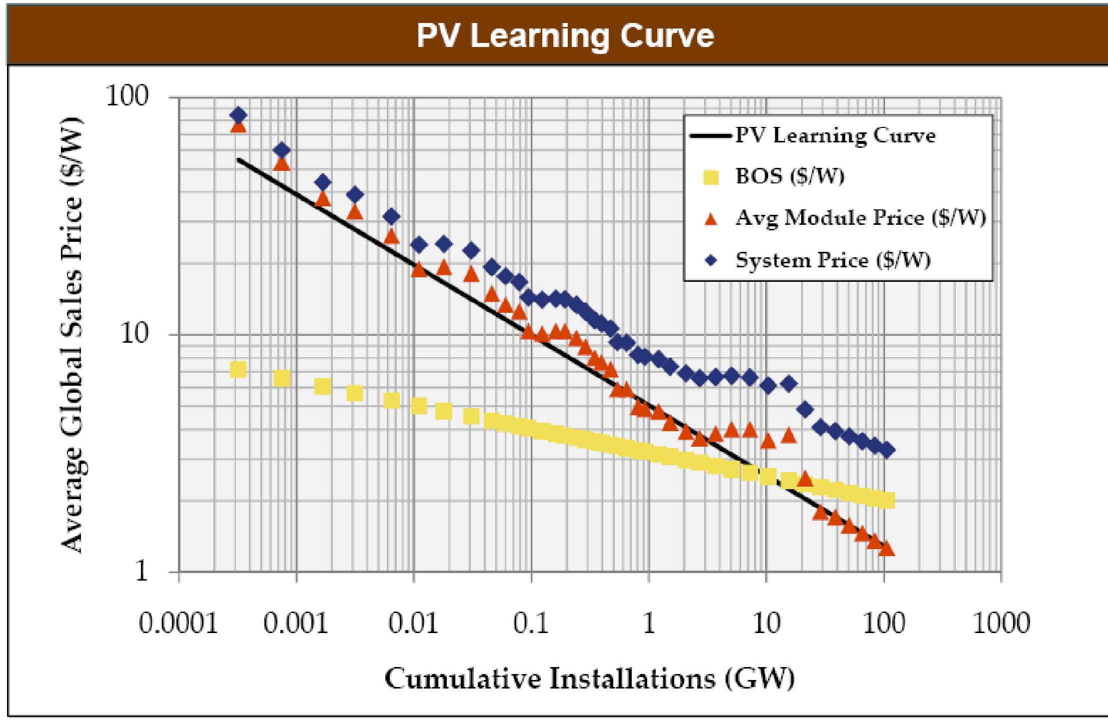
Goal : 1$/W by 2017

for 5 MW PV Plant

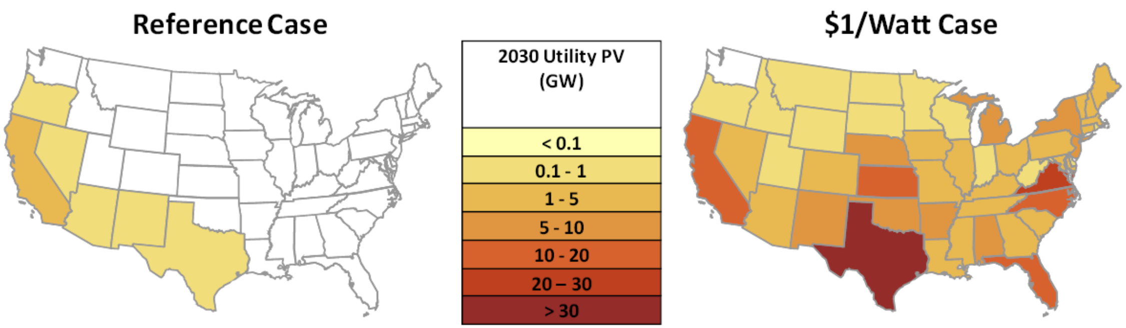
- ***$0.5/W – PV module***
- ***$0.4/W – BOS***
- ***$0.1/W – Power electronics***

Smart Grid Functionality

- ***High Penetration***
- ***Enhanced Grid Value***



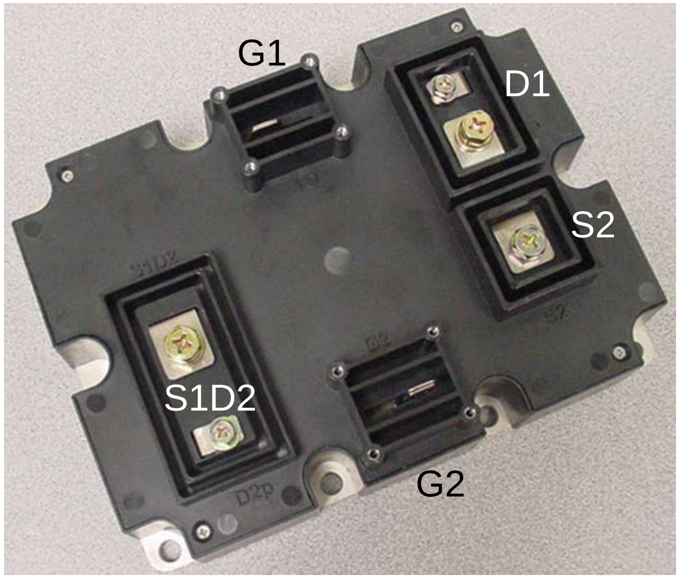
Source: Navigant Consulting

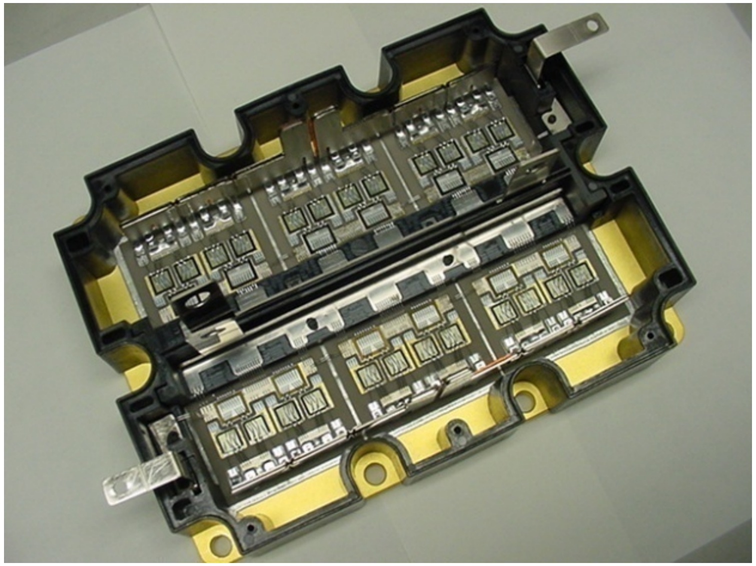


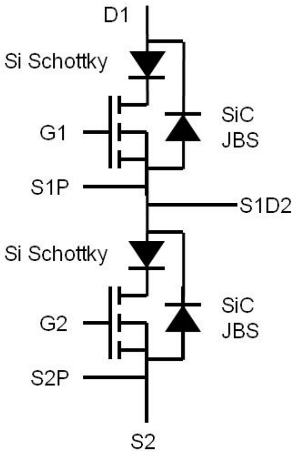
$1/W achieves cost parity in most states!

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

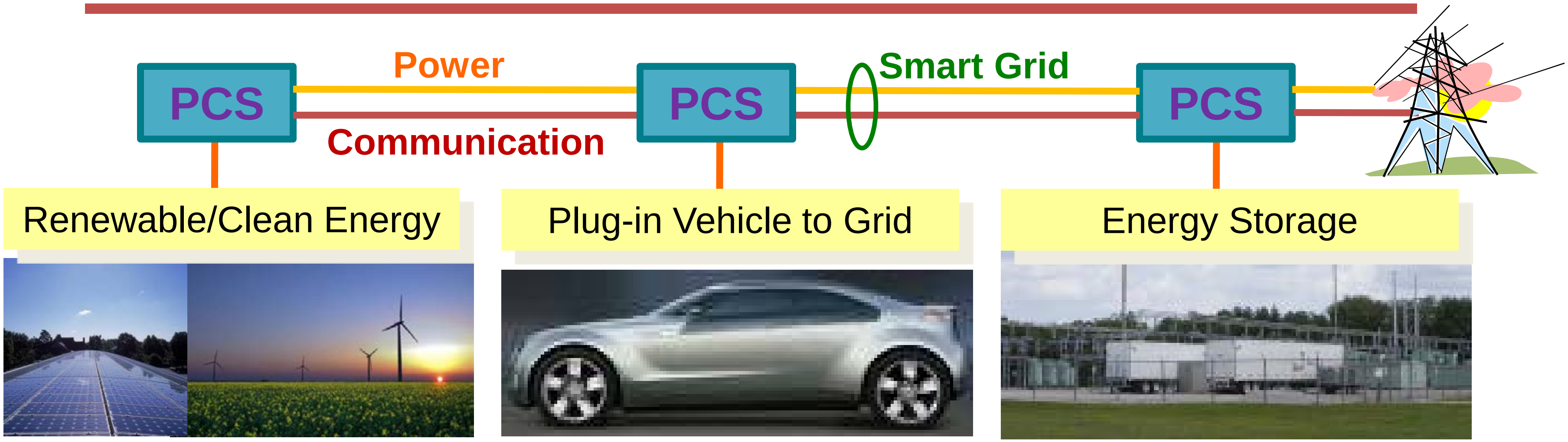






Contributed by: Leo Casey (Google)

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

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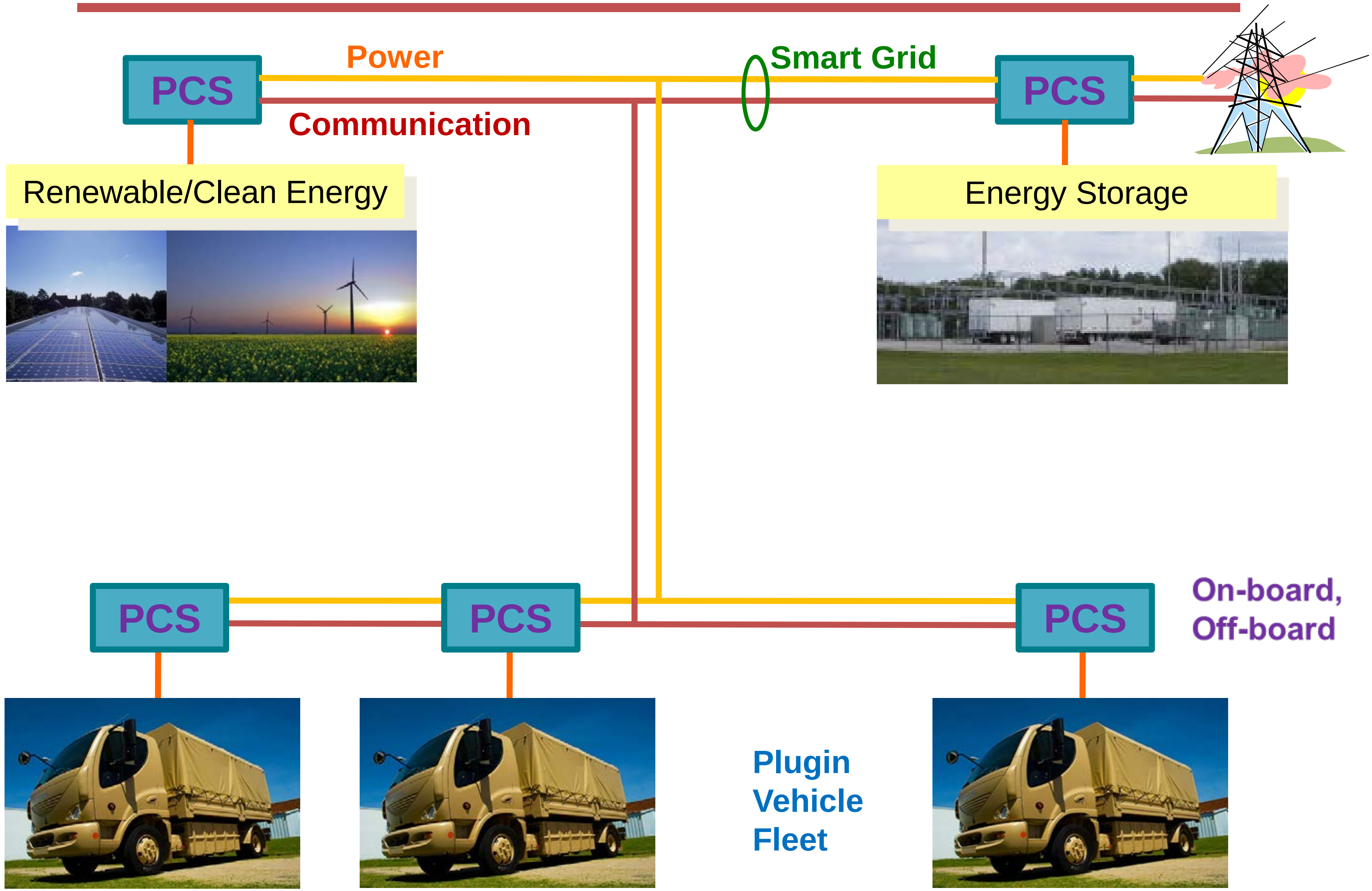
PCS Architectures for PEV Fleet as Grid Storage



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

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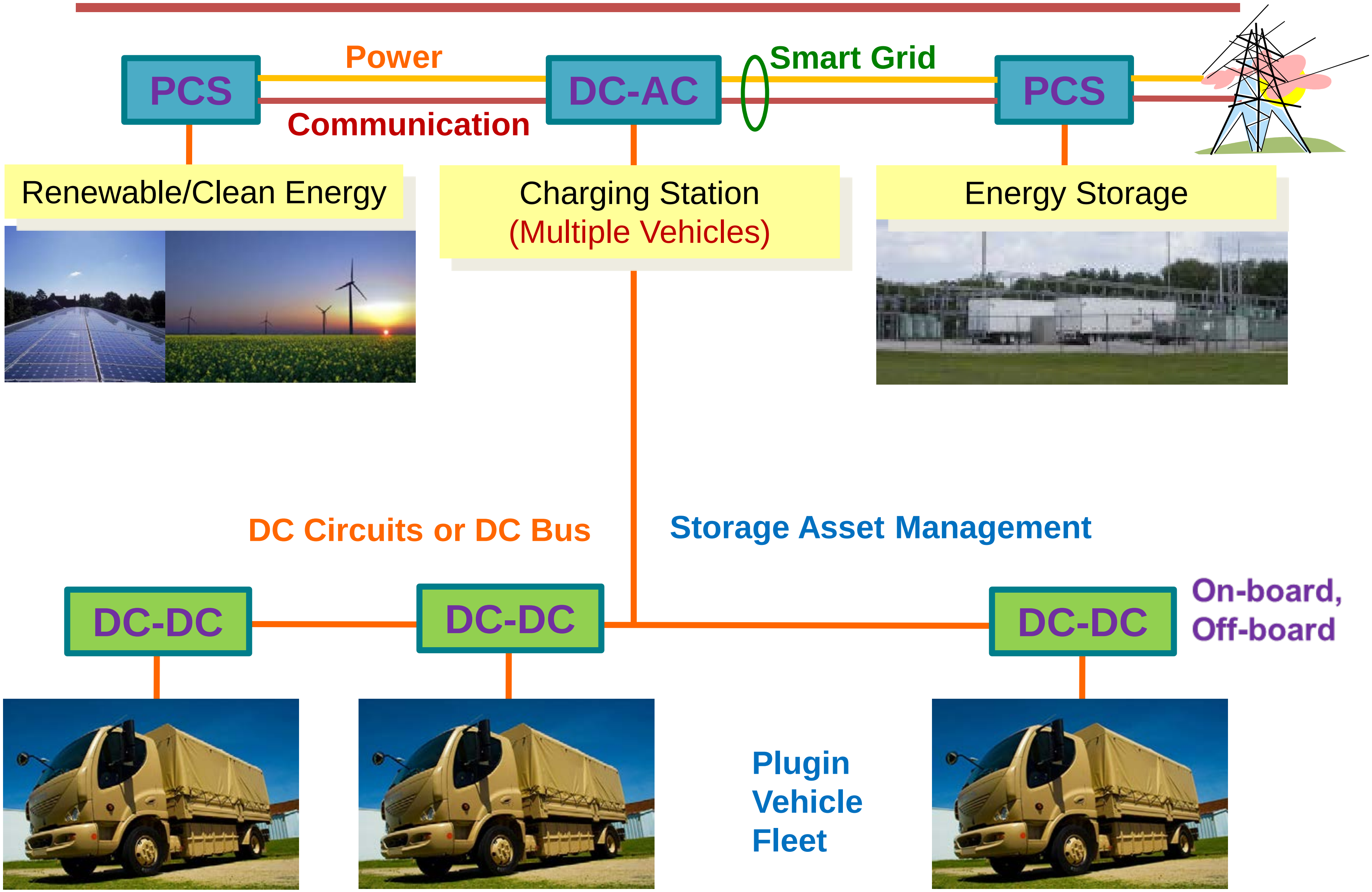
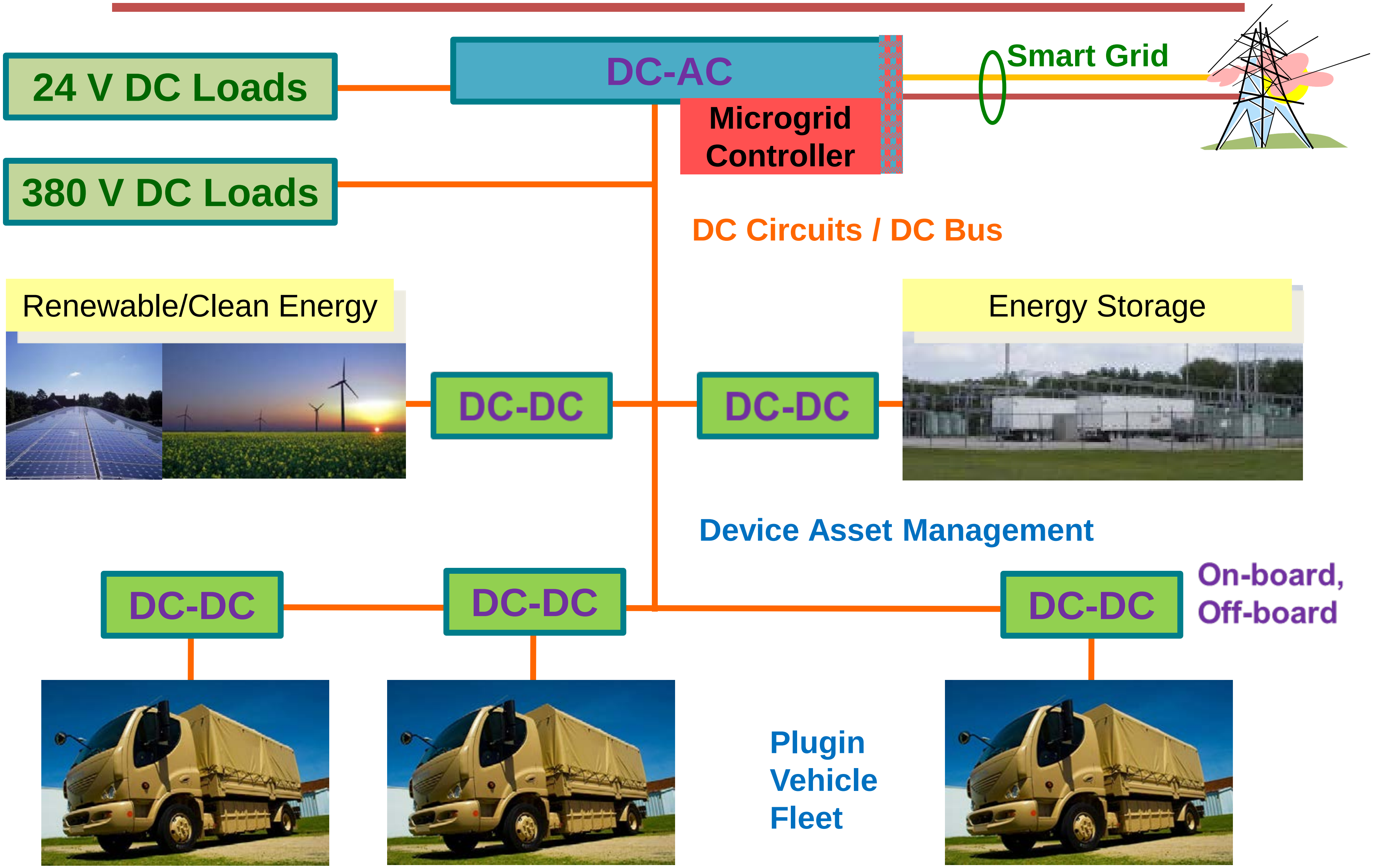
Single Large Inverter with DC Circuits to PEV Fleet



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

DC Microgrid: DC-AC with DC Circuits



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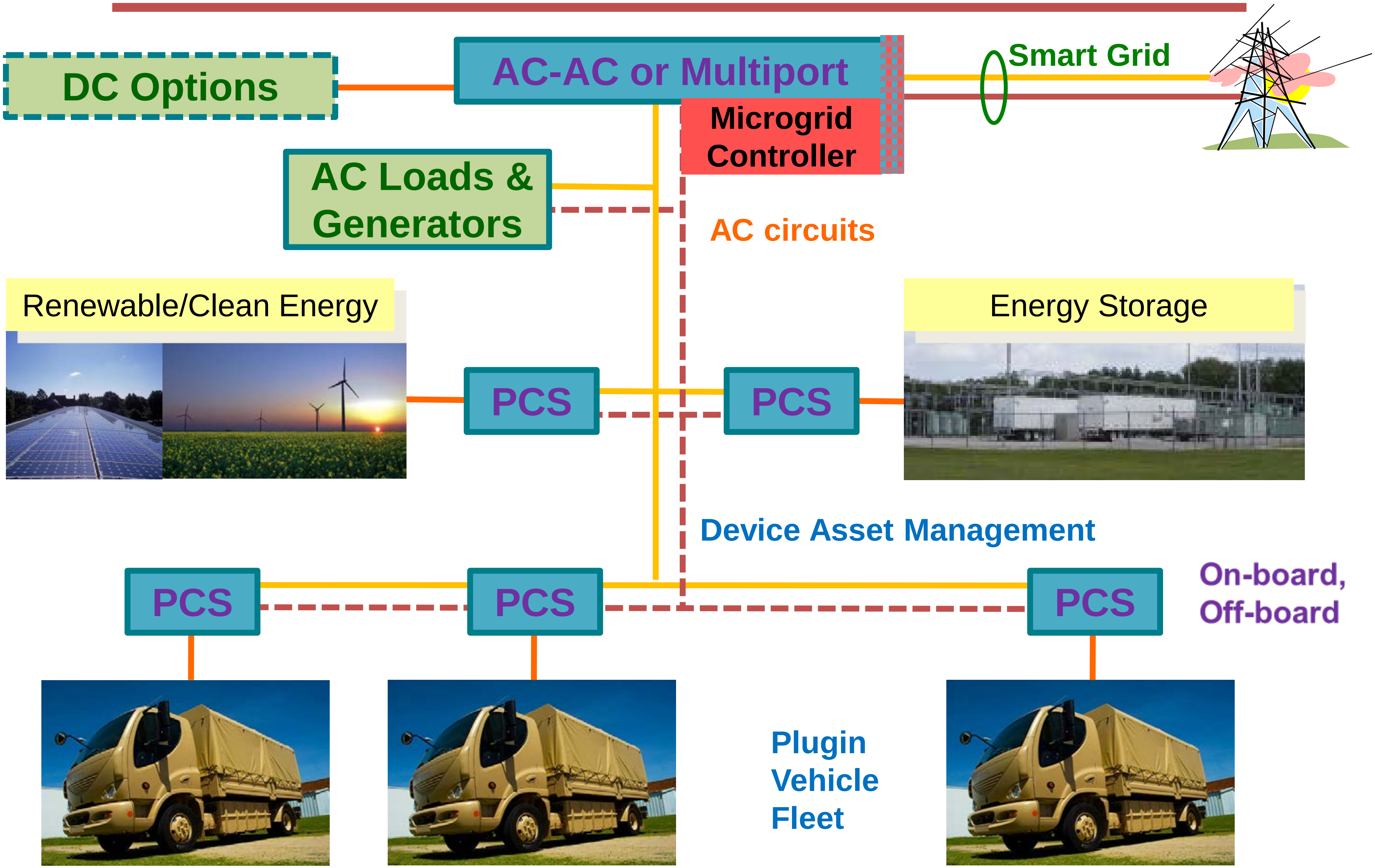
Flow Control Microgrid: AC-AC with AC Circuits



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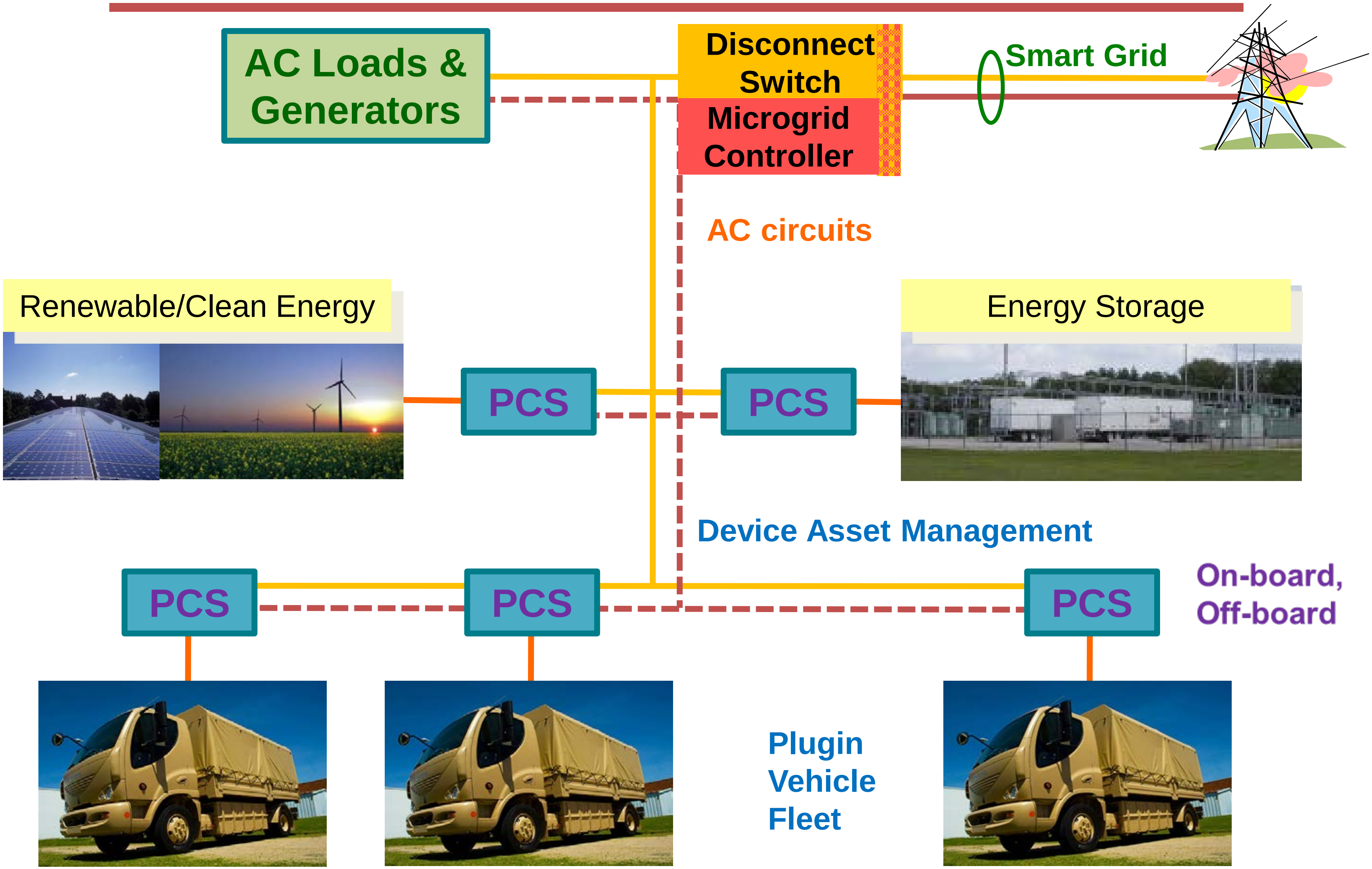
Synchronous AC Microgrid: Disconnect and Local EMS



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High-Megawatt Variable-Speed Drive Motors

A significant reduction of energy consumed world-wide could be achieved by transitioning large-power motor applications to VSD motors:

- Approximately 14% of the total electricity consumed in the United States flows through large-power electric motors (1-50 MW); e.g., for COG industry
- Many of these motors drive 10,000 to 20,000 RPM mechanical loads through a large gearbox and use mechanical throttles rather than power-electronics based VSDs.

The Previous April 2014 Workshop defined potential benefits of advanced HMW machine technology, front end power electronics, and their integration. These include:

- High-Electrical-Speed Direct-Drive Motors (high-speed VSD and machine would eliminate need for large gear box and mechanical throttles)
- "Transformer-less" Medium-Voltage Drives (small, high frequency transformer integrated within the VSD would replace large 60 Hz grid-step-down transformer)
- Integrated Motor-Drive System (grid-to-load system delivered as one unit would reduce size, weight, and cost)

Goal of Today's September 2014 Workshop: is to roadmap machine designs/concepts, power conditioning system (PCS) architectures, and advanced technologies needed to implement the most promising approaches; and define how to quantify benefits.

http://www.nist.gov/pml/high_megawatt/april-2014_workshop.cfm

Key Questions to address during Today's Workshop

1) **What are cost/performance metrics that would quantify the benefits of <u>megawatt scale</u> integrated direct-drive high-seed motor system solutions (grid interface, high-speed MV drive, and gearless high-speed motor - <u>10,000 -20,000 rpm</u>) versus today's baseline solution?**

    1a) What are representative cost per megawatt metrics for each stage of today's baseline solution, and what is expected total cost reduction for an integrated system and how would it be quantified in a proposed demonstration?

    1b) What are maintenance requirements and lifecycle cost issues for today's baseline solution, and how might proposed integrated solutions quantify lifecycle cost benefits?

    1c) What are energy loss components of today's baseline solution, and how might proposed integrated solutions quantify efficiency benefits?

    1d) What are footprint reduction metrics that would best quantify the benefits of the integrated solution?

    1e) What are factors that would need to be demonstrated to insure scalability of new solutions to high-volume low-cost manufacturing?

Key Questions to address during Today's Workshop

2) **What are key milestones for the required HMW power electronics/machine technology development needs?**

3) **How will integrated direct-drive high-speed motor systems scale to <u>high-megawatt</u> (>30MW) and what are future markets (10 years) for these systems?**

   3a) What are the applications for >10 MW motors (e.g., in oil and gas)?

   3b) What are system specifications and performance requirements for larger >10MW motors (e.g., application speed requirement might be <u>3,000-4,000 rpm</u> versus 10,000-20,000 rpm for 1 MW applications?

   3c) What are additional technology needs to ensure scalability to high MW (e.g., higher voltage semiconductors >15 kV, power electronics topologies, machine types, etc.)?