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

Advanced Power Electronics and Electric Motors (APEEM) R&D Program Overview

Office Of Vehicle Technologies

Susan Rogers

Technology Development Manager

2011 DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Program AMR and Peer Evaluation Meeting

May 10, 2011

Project ID: APE00A

HES Team Structure

APEEM CHARTER:

Develop Advanced Power Electronics and Electric Motor technologies to enable large market penetration of electric drive vehicles.

Hybrid and Electric Systems (HES) Team

David Howell, Team Lead

Vehicle and Systems Simulation & Testing

Advanced Power Electronics & Electric Motors

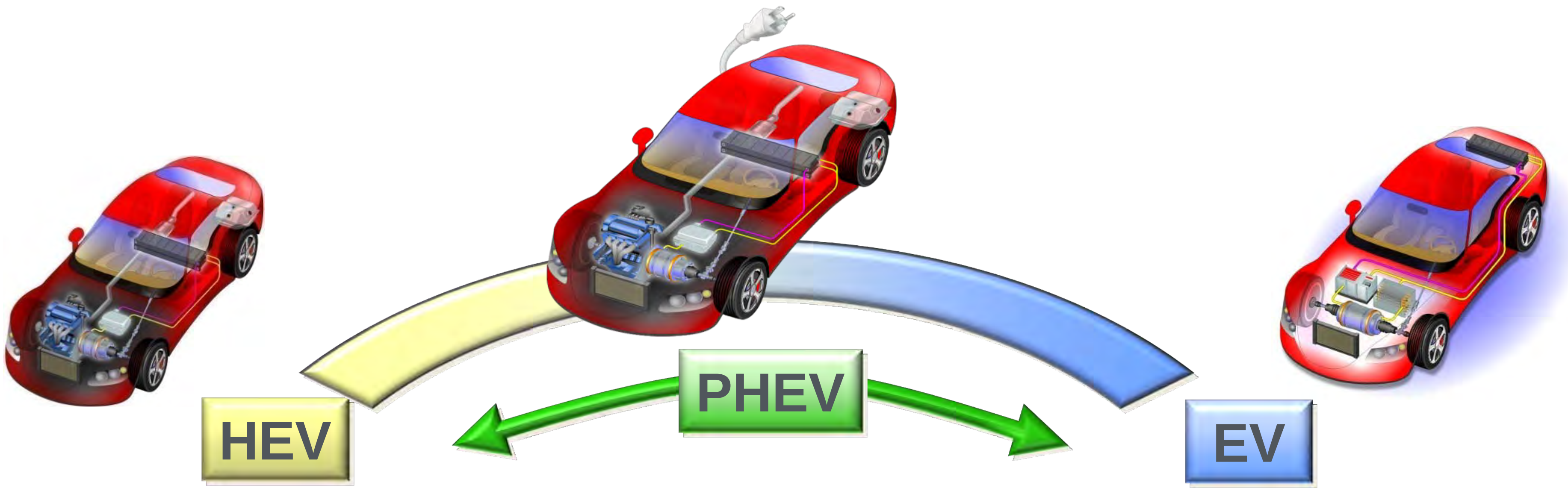
Susan Rogers & Steven Boyd

Energy Storage

APEEM Activity Covers the Full Range of Vehicle Electrification Applications

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

APEEM (Advanced Power Electronics and Electric Motors)

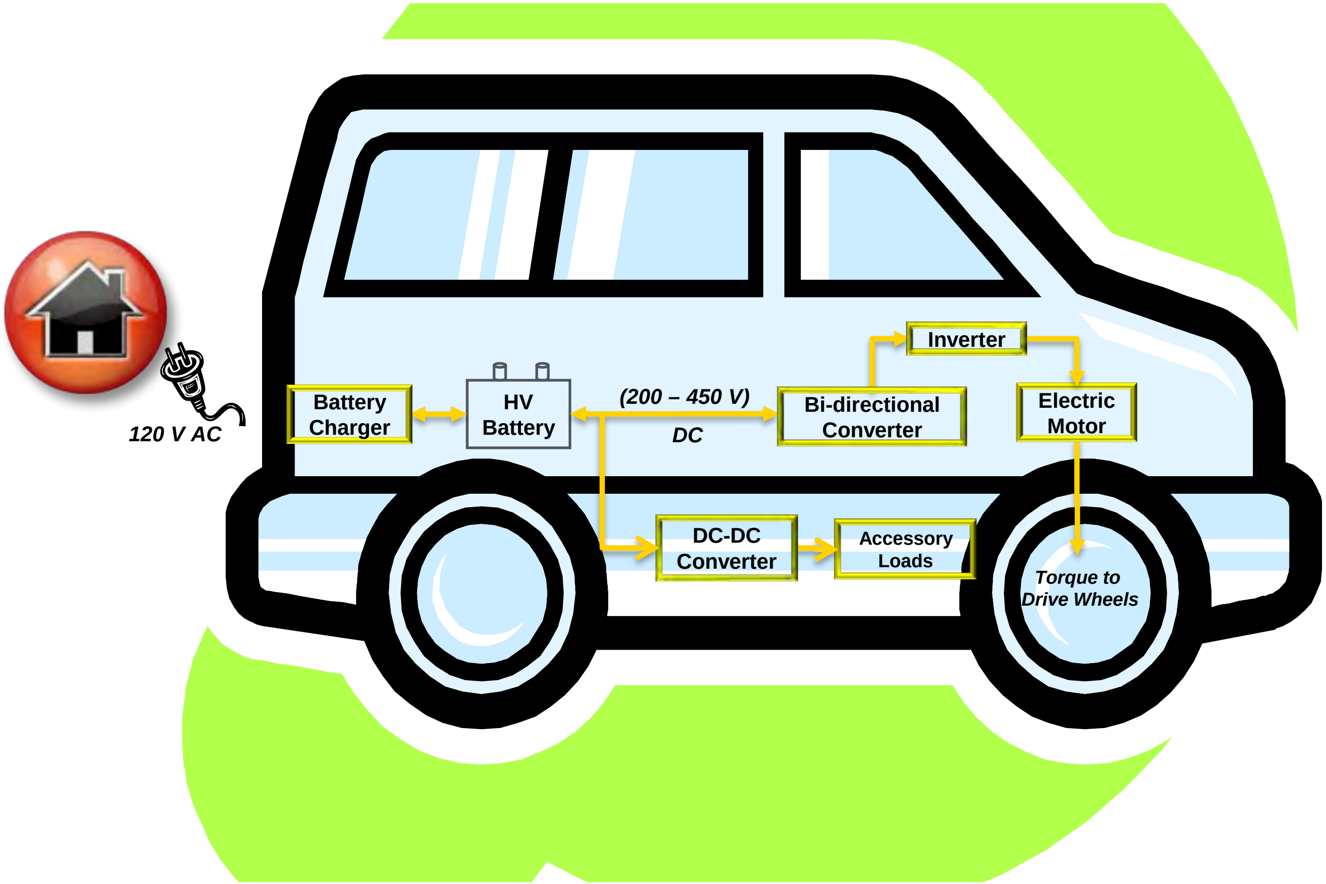


Blended ICE/Electric
- Power requirement ≥ 55 kW
- Parallel architecture
- Intermittent short operation

Sized for Electric Only
- Power required increases (up to 200 kW)
- Series architecture
- Always “on”

PHEV Position in Spectrum Depends on Design

APEEM Components are Critical and Unique to Electric Drive Vehicles



Current power electronics and electric motor technologies must advance to achieve lower cost, smaller and lighter footprints, and higher efficiency to meet marketplace demands.

Traction Drive Components
(varies with vehicle architectures)

- *Battery charger* – PEVs require a battery charger.
- *Bi-directional converter* – step up the battery voltage for the motor and step down the bus voltage for regeneration to the battery.
- *Inverter* – convert direct current (DC) to alternating current (AC) to provide phased power for vehicle traction motors and generators.
- *Electric motor* - provide power for driving.

Power Management
(varies with vehicle architectures)

- *DC-DC converter* – provides power to auxiliary vehicle buses to operate accessories, lighting, air conditioning, brake assist, power steering, etc.

APEEM Research Targets, Challenges, and Research Areas

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

Reduce Dependence on Oil

Via Electrification of Vehicle Drives

Requirements: 55 kW peak for 18 sec; 30 kW continuous; 15-year life

Technical Targets

Year	Traction Drive System			
	($/kW)	(kW/kg)	(kW/l)	Efficiency
2010	19	1.06	2.6	>90%
2015	12	1.2	3.5	>93%
2020	8	1.4	4	>94%

=

Year	Power Electronics		
	($/kW)	(kW/kg)	(kW/l)
2010	7.9	10.8	8.7
2015	5	12	12
2020	3.3	14.1	13.4

+

Year	Motors		
	($/kW)	(kW/kg)	(kW/l)
2010	11.1	1.2	3.7
2015	7	1.3	5
2020	4.7	1.6	5.7

Challenges

Research Areas

Traction Drive System

- Benchmarking technologies
- Innovative system designs

Power Electronics

- Innovative topologies
- Temperature-tolerant devices
- Packaging
- Capacitors
- Vehicle charging

Electric Motors

- Permanent magnet (PM) motors
- Magnetic materials
- High-performance non-PM motors
- New materials

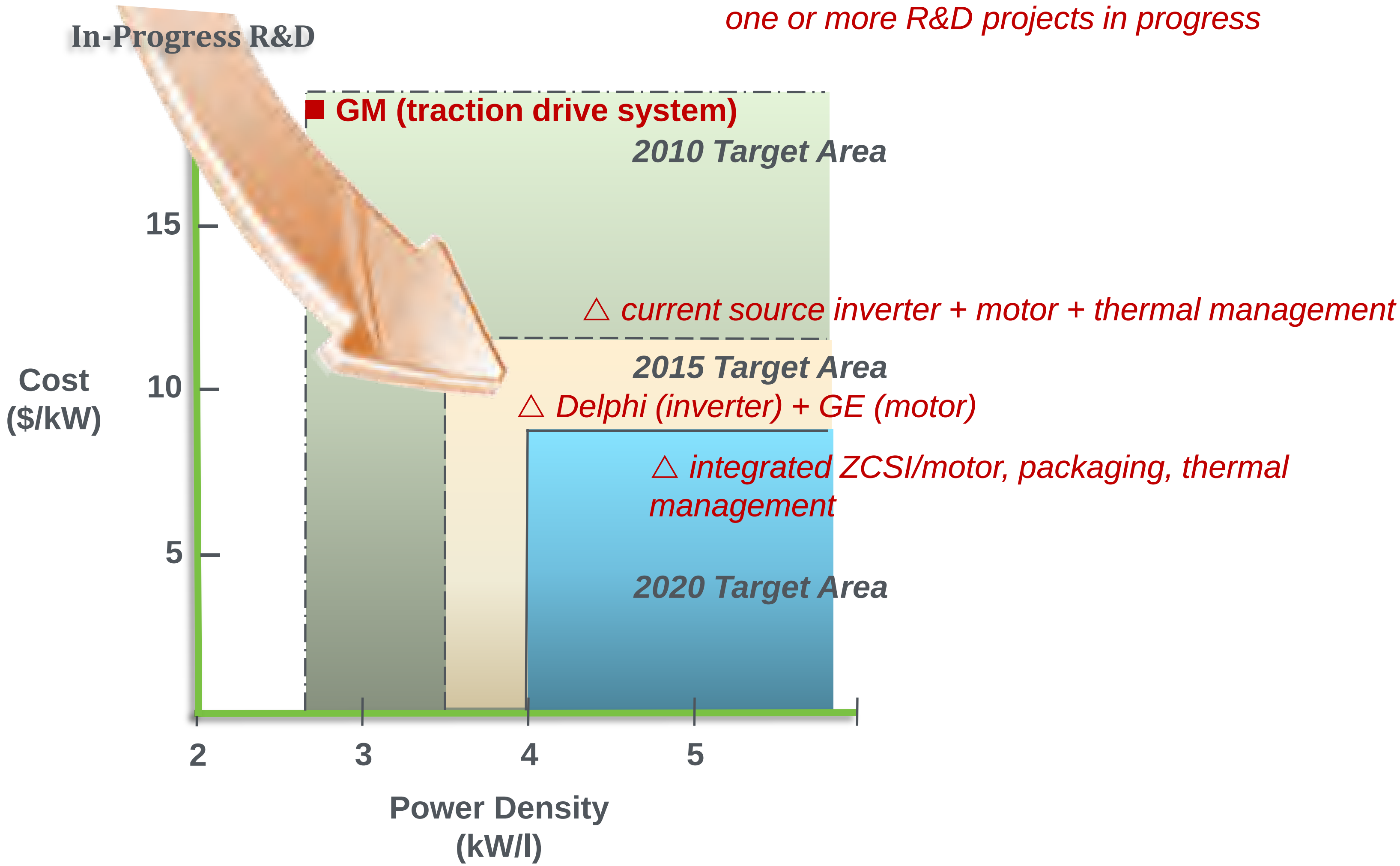
PEEM Thermal Management

- Thermal system integration
- Heat transfer technologies
- Thermal stress and reliability

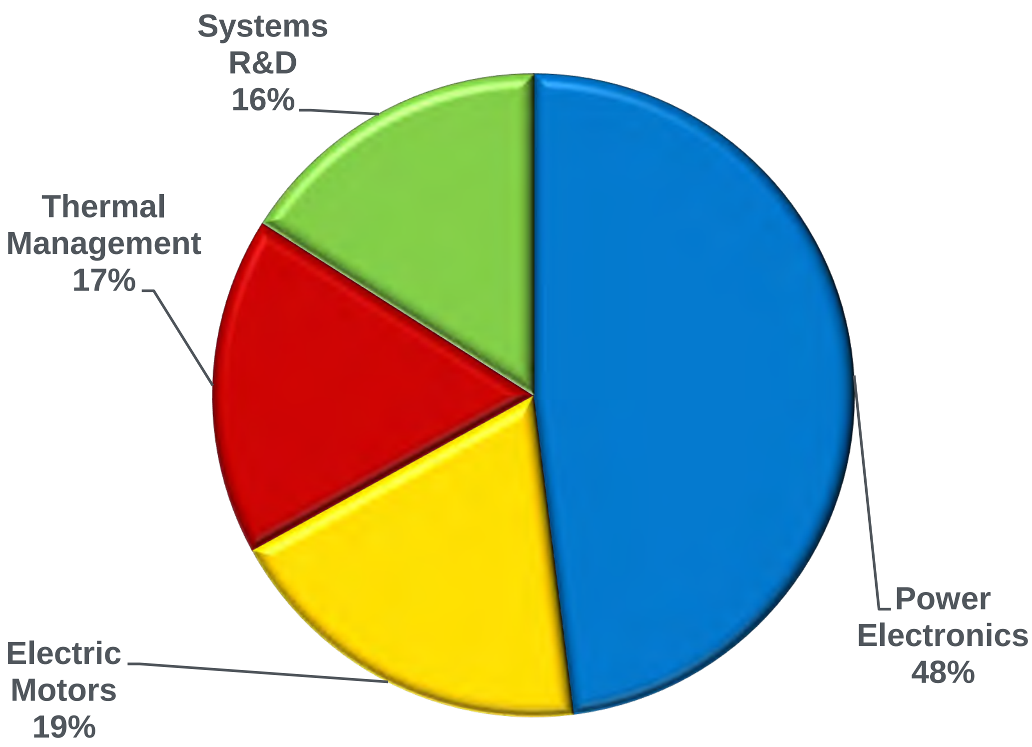
If Current Portfolio Meets All Project R&D Goals, 2020 Targets May be Achievable

■ **Results for system development project in progress**

△ *"virtual" systems modeled using goals from one or more R&D projects in progress*

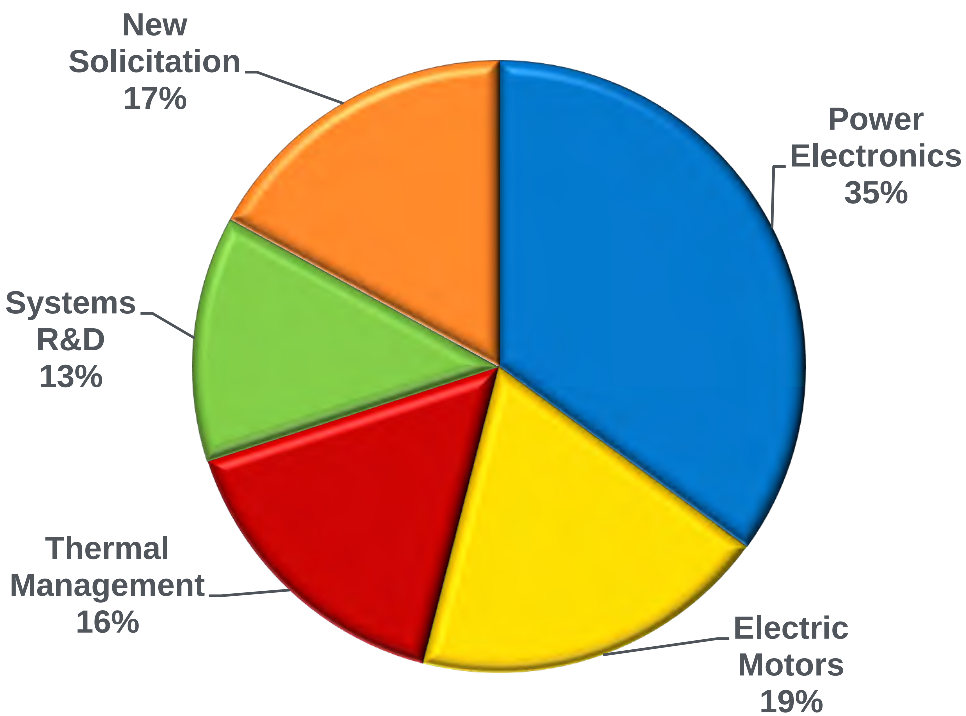


Budget History



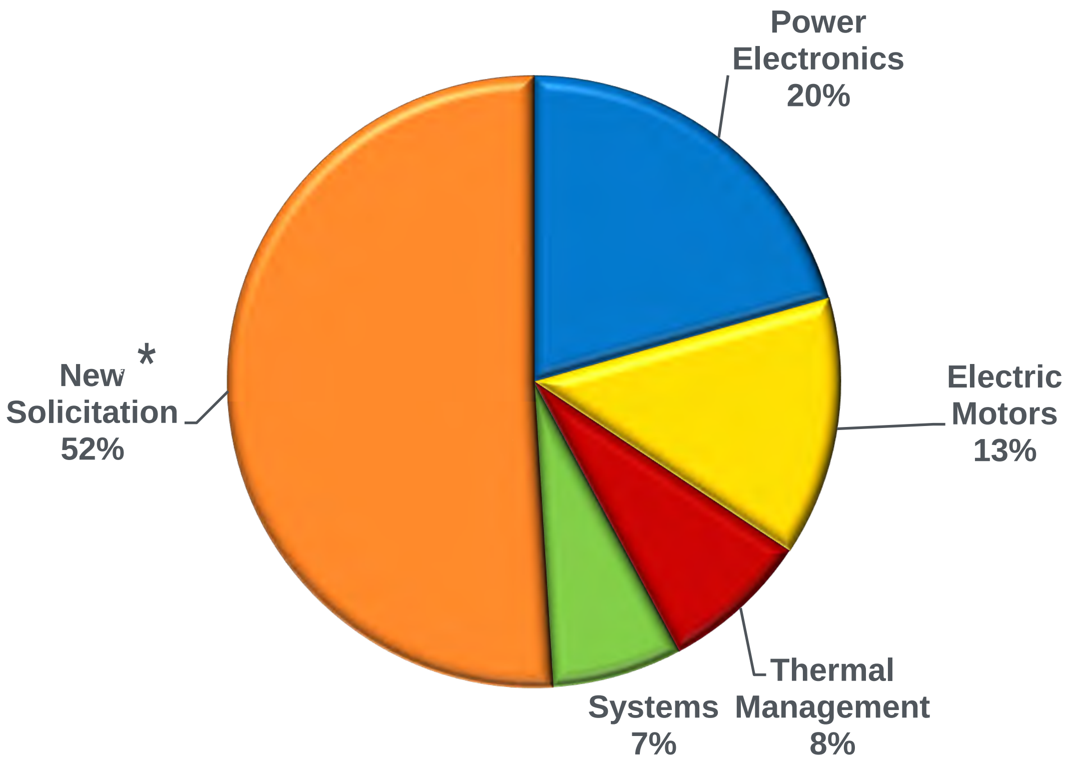
FY10 Appropriation: $22,295,000

Budget History



FY11 Request: $23,937,000

Budget History



FY12 Request: $46,656,000

* Emphasis on competitively awarded research and development of electric vehicle drive system R&D efforts focusing on a system-level design

Program Flow Advances APEEM Technologies to the Marketplace

Technical Target Input	Technology Development	Module Development
EE Tech Team	*National Laboratories*	*Industry*

Interactions with Others (e.g., IAPG, Office of Science, Solar, Wind)

Technical Target Input

- DOE
- Chrysler
- Ford
- General Motors

Technology Development

- Ames Laboratory
- Argonne National Laboratory
- Oak Ridge National Laboratory
- Sandia National Laboratories
- National Renewable Energy Laboratory
- National Aeronautics and Space Administration
- National Institute of Standards and Technology
- Advanced Research Projects Agency (ARPA-E) Activities
- Small Business Innovative Research Grants (SBIR)
    - Phases I, II, & III

Module Development

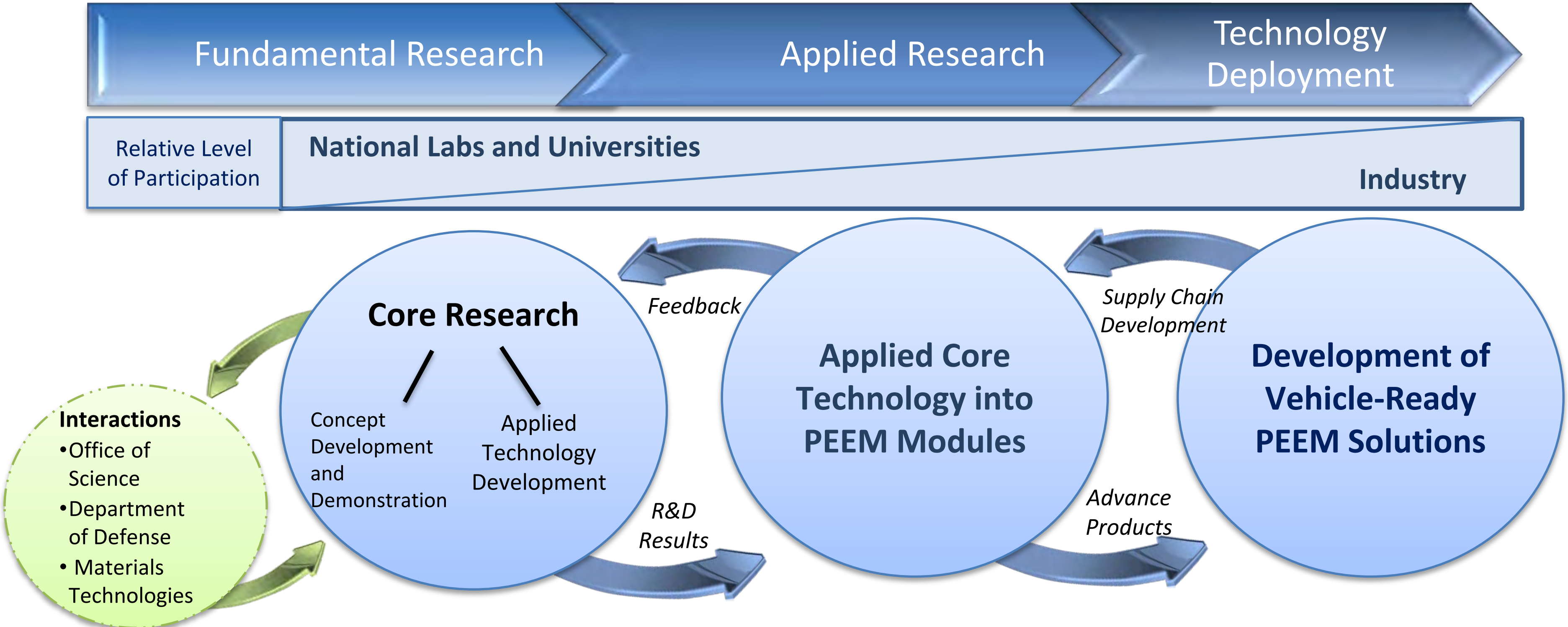
- General Motors
- Delphi Automotive Systems
- GE Global Research

- American Recovery and Reinvestment Act (ARRA) Awards

Advancing Power Electronics and Electric Motors

More Fuel Efficient Vehicles on the Road

APEEM Program Structure



- Develop technology that enables module/system advances

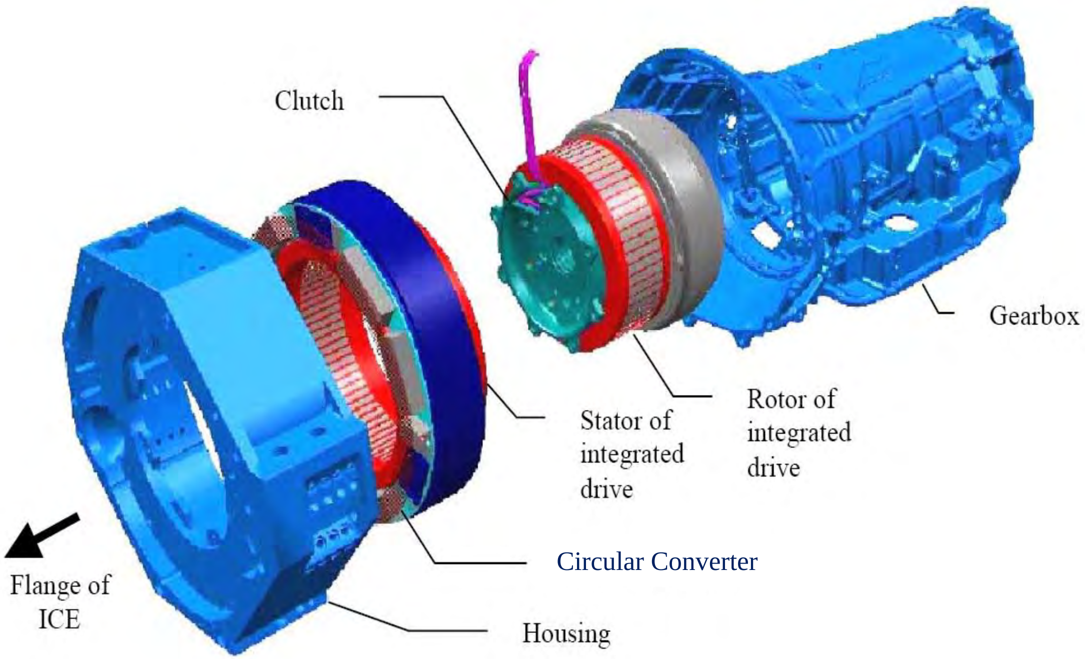
- Integrate core “technologies” into PEEM modules (inverters, converters, etc.)
- Address manufacturing aspects of core technologies
- Facilitate commercialization
- Create industrial champions
- Develop supply chain insertion mechanism

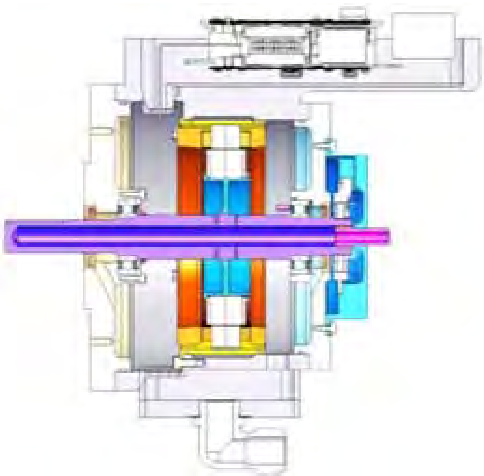
- Develop practical methods for producing inverters, motors, converters, or traction systems that incorporate advanced technologies

Research Focus Areas

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

Traction Drive System	
Focus Area	**Benefits**
Innovative Systems Design *(Meet future system targets)*	Modular and integrated solutions to meet size, weight, and cost 2015 and 2020 targets for drive system.
Benchmarking *(Program planning)*	Vital to program planning and project performance activities.



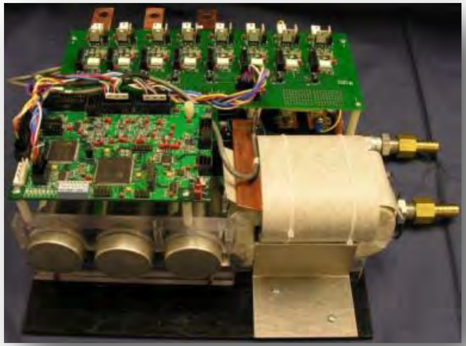


Integrated Motor and Inverter Concept

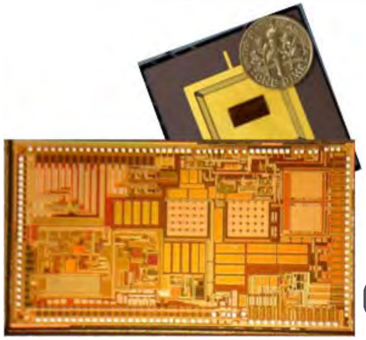
Research Focus Areas

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

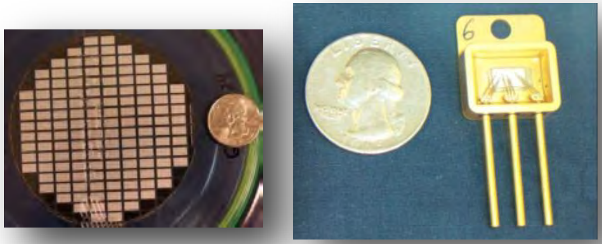
Power Electronics	
Focus Area	**Benefits**
New Topologies for Inverters and Converters *(Decrease size, cost, and improve reliability)*	Avenue to achieve significant reductions in PE weight, volume, and cost and improve performance. • Reduce capacitance need by 50% to 90% yielding inverter volume reduction of 20% to 35% and cost reduction. • Reduce part count by integrating functionality thus reducing inverter size and cost and increasing reliability. • Reduce inductance, minimize electromagnetic interference (EMI) and ripple, reduce current through switches all result in reducing cost.
Temperature – Tolerant Devices *(Wide Bandgap Semiconductors)*	Produces higher reliability, higher efficiency, and enables high-temperature operation.
Packaging *(Greatly reduced PE size, cost, and weight with higher reliability)*	Provides opportunity for greatly decreased size and cost • Module packaging can reduce inverter size by 50% or more, cost by 40%, enable Si devices to be used with high-temp coolant for cost savings of 25%, and enable use of air cooling. • Device packaging to reduce stray inductance, improve reliability and enable module packaging options. When coupled with heat transfer improvements gains are enhanced.
Capacitors *(Reduced inverter volume)*	Improved performance can reduce capacitor size by 25% reducing inverter size by 10% and increase temperature limit.
Vehicle Charging *(Provide function at minimum cost)*	Provide the vehicle charging function with emphasis on cost and weight minimization.



Current Source Inverter



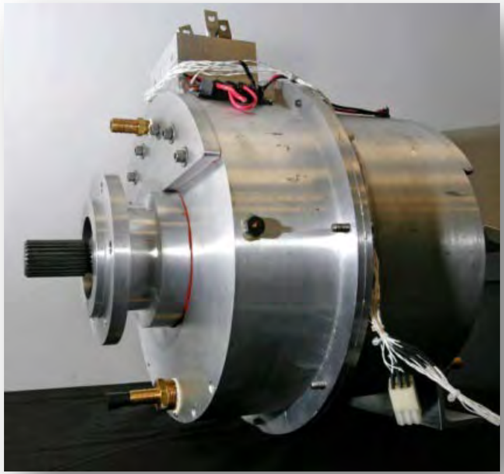
Silicon-on-Insulator Chip (chip size 10x5 mm^2)



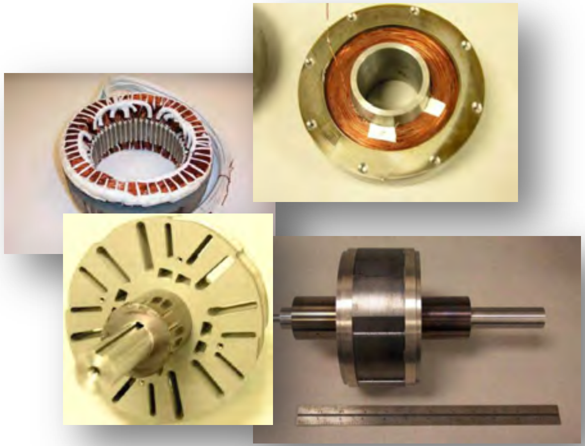
Wide Bandgap Semiconductors

Electric Motors

Focus Area	Benefits
High Performance Permanent Magnet (PM) Motors ***(Reduce cost and maintain performance)***	Cost is major concern for interior permanent magnet (IPM) motor (cost reductions of 75% are required to meet 2020 target). Work on all aspects of motor design may reduce cost by 25% to 40%.
Magnetic Materials ***(Reduce cost and increase temperature)***	Magnetic material costs are 50% to 75% of the motor targets for 2015 and 2020, respectively. Work focusing on reducing cost and increasing temperature capability could reduce motor cost by 5% to 15%.
Non-PM Motors ***(Greatly reduce cost in motor and power electronics)***	Non-PM motor technology matching the performance of IPM machines yields the greatest opportunity for motor and system cost reduction. • Eliminating PMs could reduce motor cost by 30%. • Back emf of IPM requires boost converter which adds cost; eliminating boost saves 20% in PE cost. • Reduced power factors of IPM can result in increased PE costs; optimized power factors can result in up to 15% PE cost savings.
New Materials ***(Reduce motor cost)***	New materials for laminations, cores, etc. could save 20% of motor cost.



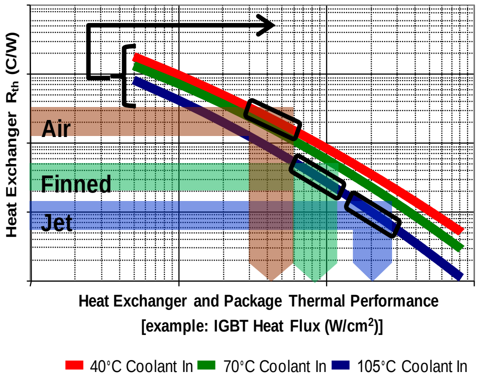
16,000 rpm Brushless Field Excitation (BFE) IPM Motor

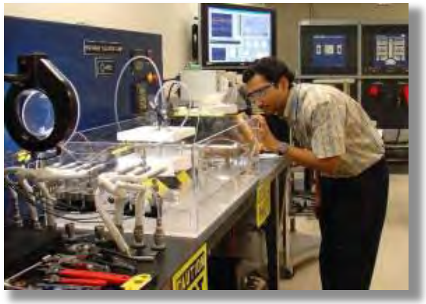


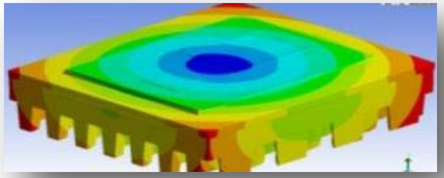
Research Focus Areas

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

Thermal Management	
Focus Area	**Benefits**
Thermal System Integration ***(Technology integration at lower system cost)***	• Guides thermal research objectives. • Defines thermal requirements. • Facilitates viable thermal solutions. • Addresses motors and balance of system. • Links thermal technologies to electric traction drive providing system-wide thermal solutions.
Heat Transfer Technologies ***(Enable increased power density at lower cost)***	• Develops and demonstrates heat transfer technologies and materials to enable program targets. • Provides detailed characterization of the thermal performance of candidate heat transfer technologies. • Creates fundamental thermal models.
Thermal Stress and Reliability ***(Assure and improve reliability of high power density, low cost technologies)***	• Develops advanced predictive thermal stress and reliability modeling tools. • Examines interconnection methodologies. • Guides research decisions, streamlines. development time, and identifies potential barriers to meeting life and reliability goals.







FY11 Emphasis

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

- **Inverter topologies to reduce cost and volume**
  - Reduce capacitor requirements
  - Integrate functionality
- **Packaging, high-temperature components, and reliability for long-term transformation technologies**
- **Motor research reducing cost and addressing rare earth material volatility**
  - Advanced magnet materials
  - Non-permanent magnet motor concepts
- **Thermal management technologies to reduce volume and cost, and enhance thermal reliability**

R&D Pathways Provide Basis for Portfolio Selection

- Pathways established using value engineering
- Each pathway contains significant technical risk and challenges
- Multiple research pathways pursued
  - mitigate technical risk and
  - address different technology needs related to vehicle architecture
- Pathways provide basis for research focus areas
- Contributions from many or all focus areas required to achieve targets; no silver bullet
- Project portfolio mapped against focus areas; all projects align with one or more focus areas

American Recovery and Reinvestment Act Projects (ARRA)

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

- **Remy, Inc -** Hybrid Electric Motors & Controls
- **General Motors Corp -** Global Rear Wheel Drive Electric Drive Units
- **Ford Motor Co** - HEV & PHEV Transaxles
- **Magna E-Car Systems of America, Inc** - Electric Drive Systems
- **Delphi Automotive Systems, LLC** - Electric Drive Power Electronics
- **Allison Transmission, Inc** - Commercial-duty Hybrid Systems
- **UQM Technologies** - Drive Electronics & Electric Motor/ Generator
- **KEMET Corp** - DC Bus Capacitors
- **SBE, Inc** - DC Bus Capacitors
- **Powerex, Inc** - Semiconductor Devices

SBIR Awards

- **Phase I**
  - **Strategic Polymer Sciences, Inc** - Advanced Film Capacitors for Power Inverters in Electric Drive Vehicles
  - **Materials & Electrochemical Research (MER) Corporation** - A Low Cost Continuous Process to Produce Magnet Alloys
  - **Advanced Thermal Technologies, LLC** - Low Thermal Resistance Integrated Package and Heat Sink for HEV IGBT Modules
  - **Applied Nanotech, Inc** - Nanomaterials for High Performance Thermal Packaging
- **Phase II**
  - **NBE Technologies, LLC** - High-Temperature Packaging of Planar Power Modules by Low-temperature Sintering of Nanoscale Silver Paste
- **Phase III**
  - **Electron Energy Corporation** - High Performance Permanent Magnets for Advanced Motors
  - **Strategic Polymer Sciences, Inc** - Compact High Temperature DC Bus Capacitors for Electric Vehicles

ARPA-E Projects Funded by DOE

ARPA-E Awards (FY11 Automotive Focus)

- **Arkansas Power Electronics International, Inc -** Low-Cost, Highly-Integrated Silicon Carbide (SiC) Multichip Power Modules (MCPMs) for Plug-In Hybrid
- **Case Western Reserve University -** High-Power Titanate Capacitor for Power Electronics
- **HRL Laboratories, LLC -** Gallium-Nitride Switch Technology for Bi-directional Battery-to-Grid Charger Applications
- **Transphorm Inc -** High Performance GaN HEMT Modules for Agile Power Electronics

- For more information: http://arpa-e.energy.gov/

Thank You