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

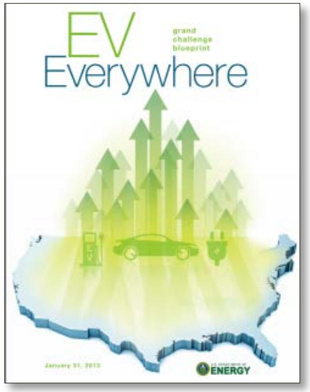
Overview of the VTO Electric Drive Technologies Program

June 9, 2015

Steven Boyd – Technology Manager
Susan Rogers – Technology Manager

Organizational Overview

USDRIVE
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

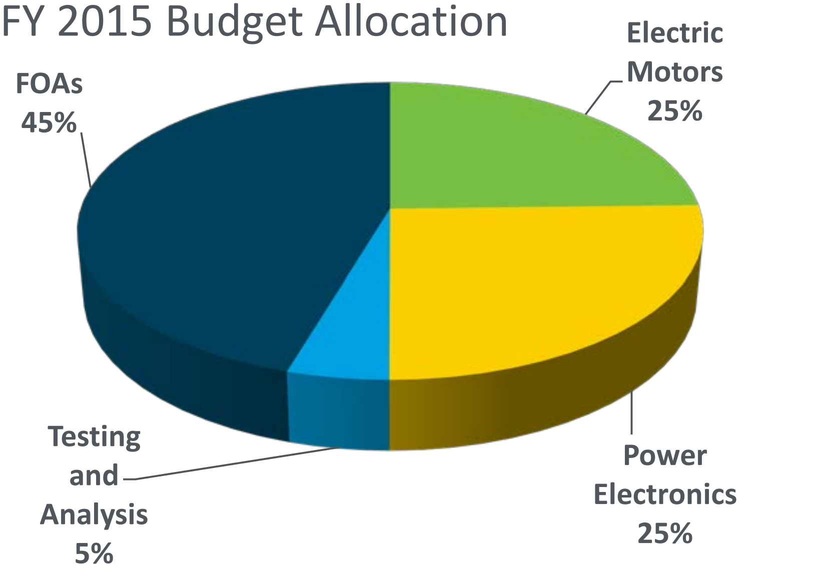


- Vehicle Technologies Office
  - Hybrid Electric Systems
    - Battery Technology R&D
    - Electric Drive Technologies (EDT) R&D
      - Industry
      - Federal Agencies
      - Academia
      - National Labs
    - Vehicle Systems

Electric Drive Technologies (EDT) Overview

The focus of the Electric Drive Technologies R&D activity is to develop technologies and designs to reduce the cost, improve the performance, and increase the reliability of power electronics, electric motors, and other electric propulsion components.

FY 2015 Budget Allocation



FY 2014	FY 2015	FY 2016 Request
$ 24 M	$ 21 M	$ 39 M

R&D emphasis accelerates:

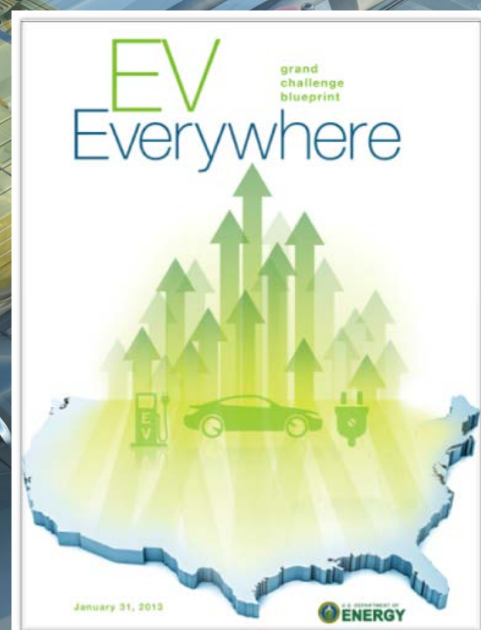
- Adoption of wide bandgap (WBG) semiconductors
- Reduction or elimination of rare earth magnets

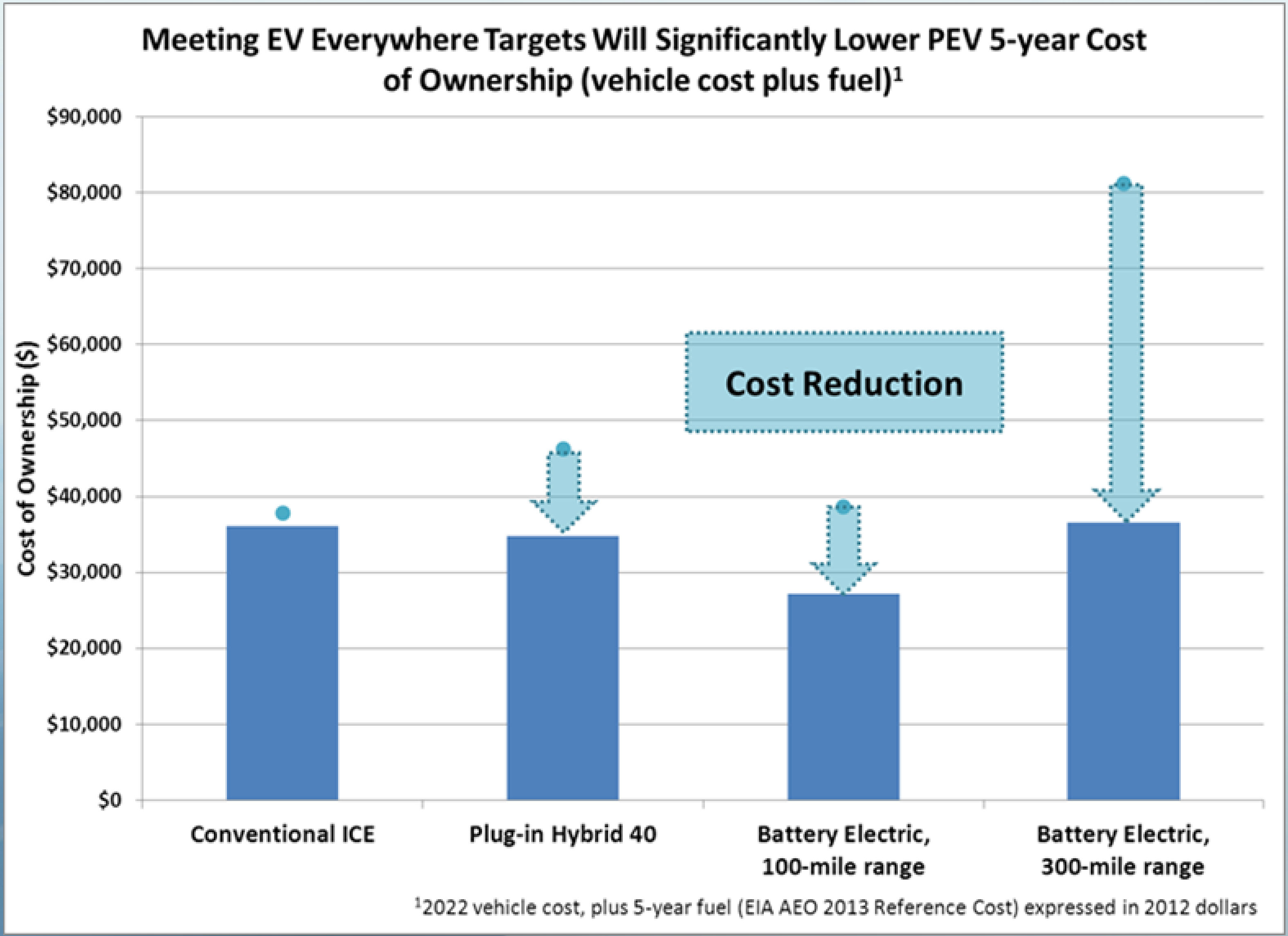
FY15 Funding Opportunity Announcement (FOA) Topics:

- Vehicle Technologies Incubator
- WBG Power Module Development

EV Everywhere Grand Challenge

A DOE Clean Energy Grand Challenge with the goal of enabling U.S. companies to produce plug-in electric vehicles that are as affordable and convenient for the average American family as today's gasoline-powered vehicles within the next 10 years (by 2022).

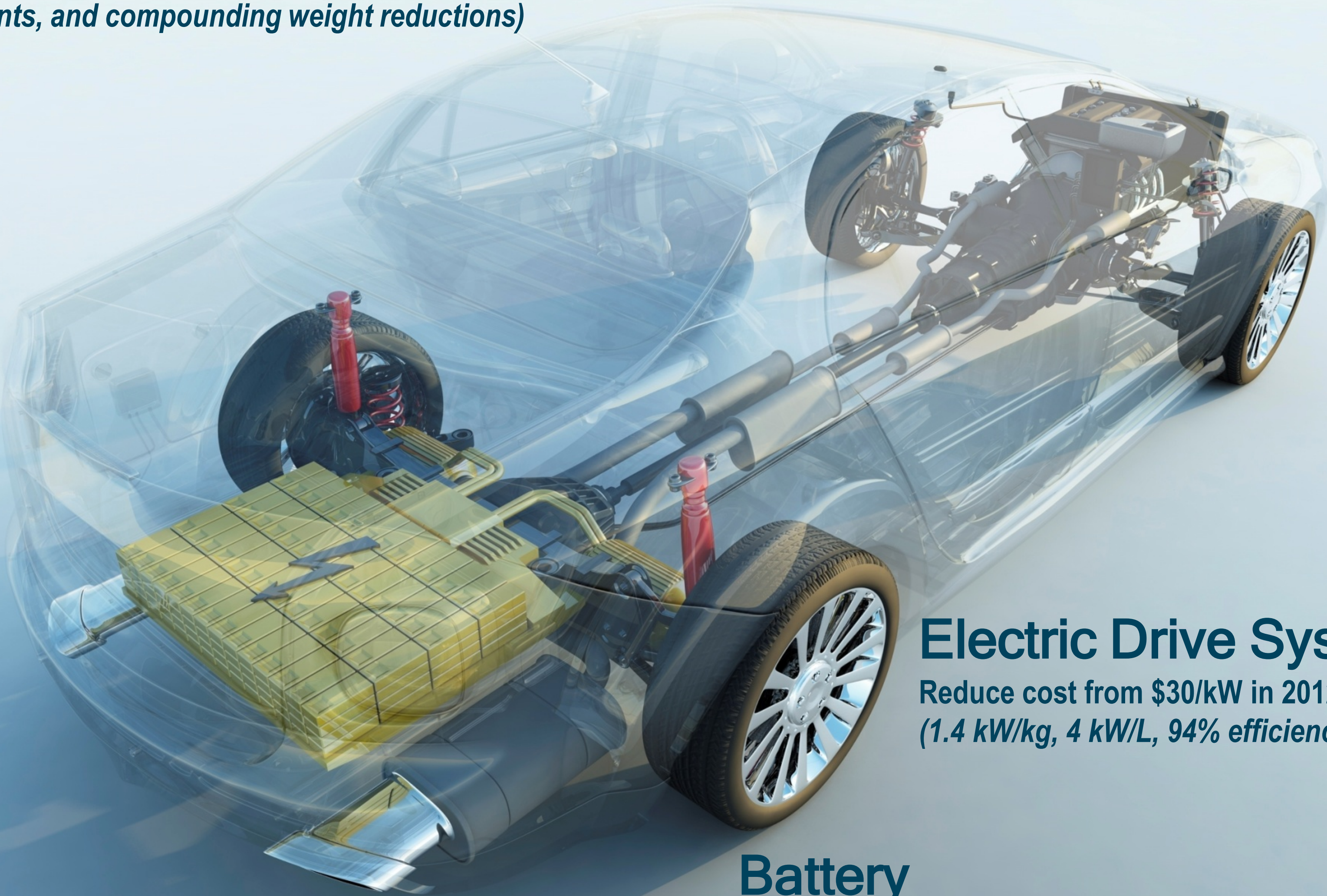




Meeting EV Everywhere Targets Will Significantly Lower PEV 5-year Cost of Ownership (vehicle cost plus fuel)[1]
$90,000
$80,000
$70,000
$60,000
$50,000
$40,000
$30,000
$20,000
$10,000
$0
Cost of Ownership ($)
Cost Reduction
Conventional ICE
Plug-in Hybrid 40
Battery Electric, 100-mile range
Battery Electric, 300-mile range
[1]2022 vehicle cost, plus 5-year fuel (EIA AEO 2013 Reference Cost) expressed in 2012 dollars

Vehicle Weight Reduction

Reduce vehicle weight by nearly 30%
(Includes body, chassis, interior, electric drive components, and compounding weight reductions)



Electric Drive System

Reduce cost from $30/kW in 2012 to $8/kW
(1.4 kW/kg, 4 kW/L, 94% efficiency)

Battery

Reduce cost from $500/kWh in 2012 to $125/kWh
(250 Wh/kg, 400 Wh/L, 2 KW/kg)

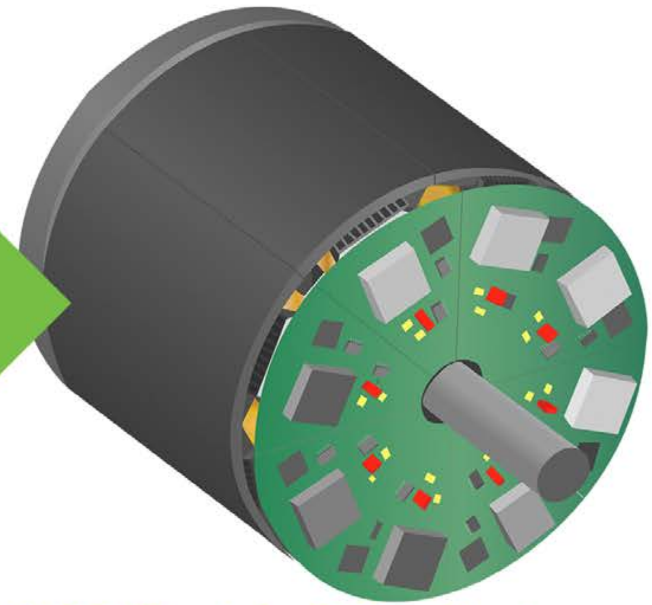
Detailed EV Everywhere Targets for Electric Drive System

4X Cost Reduction

35% Size Reduction

40% Weight Reduction

40% Loss Reduction



2012 Electric Drive System

$30/kW, 1.1 kW/kg, 2.6 kW/L

90% system efficiency

(on-road status)

- Discrete Components
- Silicon Semiconductors
- Rare Earth Motor Magnets

2022 Electric Drive System

$8/kW, 1.4 kW/kg, 4.0 kW/L

94% system efficiency

(R&D status)

- Fully Integrated Components
- Wide Bandgap Semiconductors
- Non-rare Earth Motors

2015 Electric Drive System

$12/kW

(R&D status)

Research Partnerships Accelerate Implementation of Innovation

NATIONAL LABORATORIES

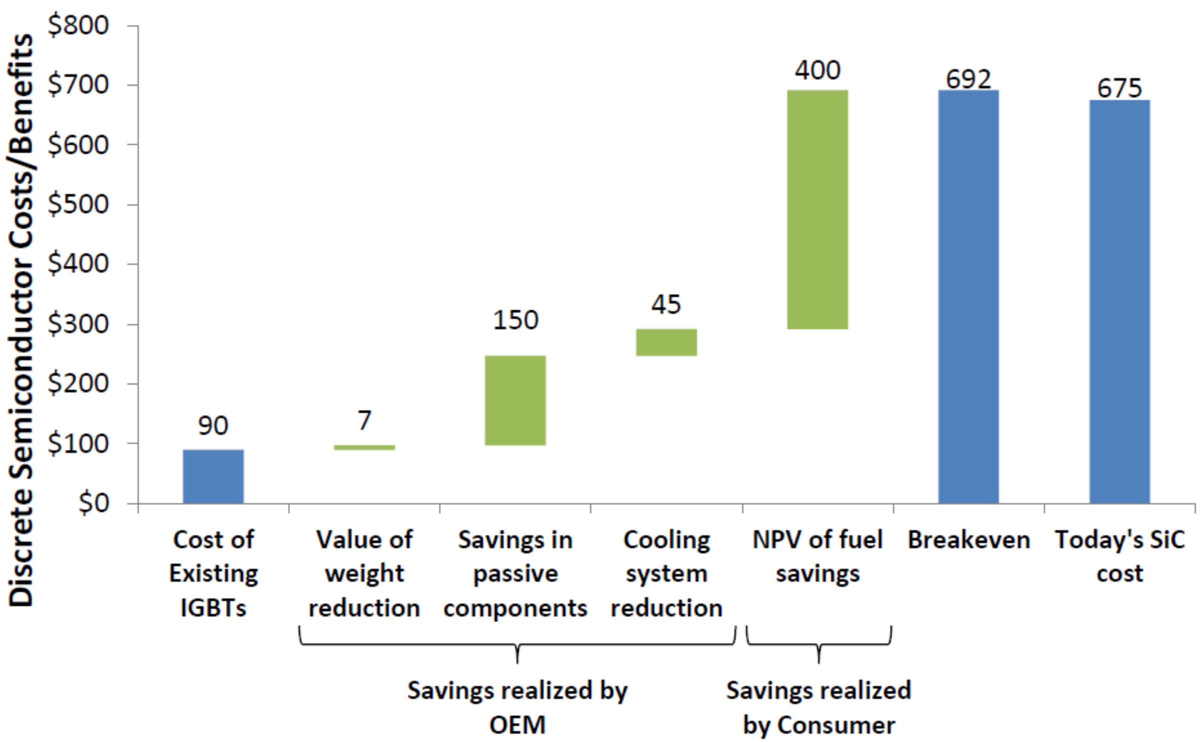
- Engineered materials
- Novel integrated topologies
- Packaging technologies & concepts
- Emerging electronic devices
- Additive manufacturing
- Supercomputing

INDUSTRY

- Integrates innovations
- Commercializes technology
- Creates American jobs
- Reduces emissions
- Saves energy

R&D Focus Area: Wide Bandgap Semiconductors (WBGs)

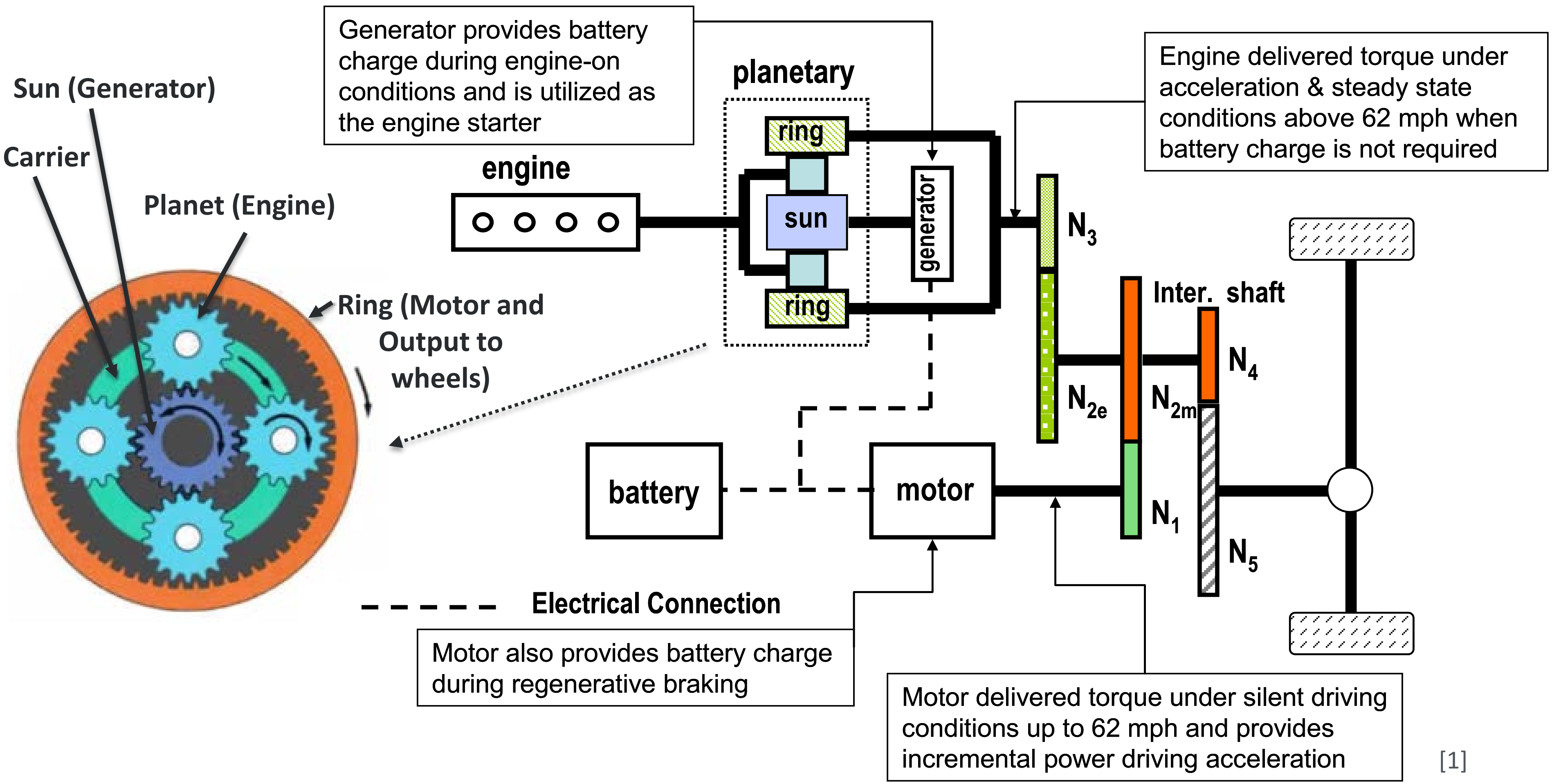
- Reduced energy "costs"
  - Increased efficiency
  - Less losses, heat, size
- Higher power density (smaller volume)
  - Higher switching frequencies
  - Higher temperatures
  - Less cooling needed
- Higher switching frequency
  - Smaller passives
  - Associated decrease in weight, volume, cost
- Lower system cost
  - Higher device cost
  - Lower system cost
  - Potential for future cost reduction in WBG semiconductors



Cost-effectiveness of SiC transistors over IGBTs for HEV inverters based on the entire value chain [1]

[1] McKinsey & Company. (2012). Unleashing Growth in Wide Bandgap : The upcoming disruptions in power 629 electronics. In GSA Semiconductor Leaders Forum Taiwan.

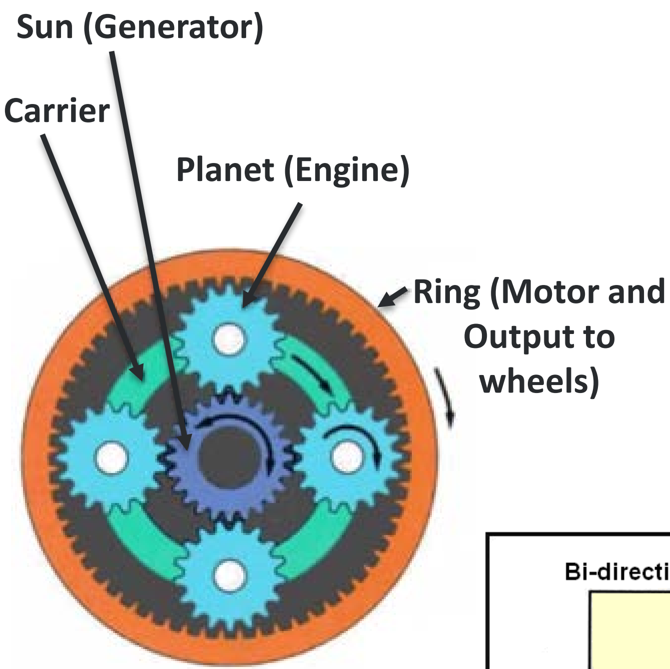
R&D Focus Area: Wide Bandgap Semiconductors (WBGs)

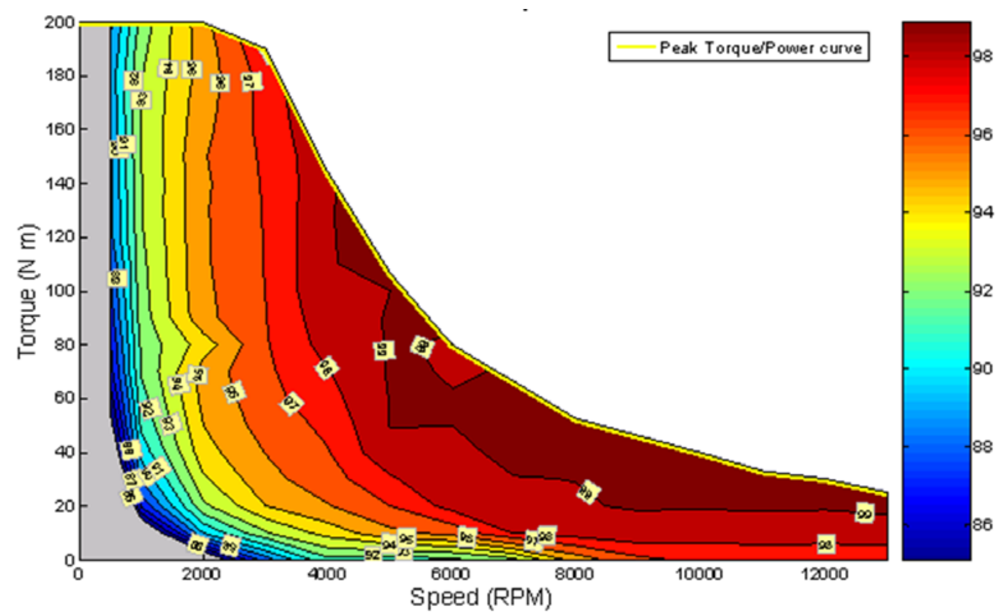


[1]

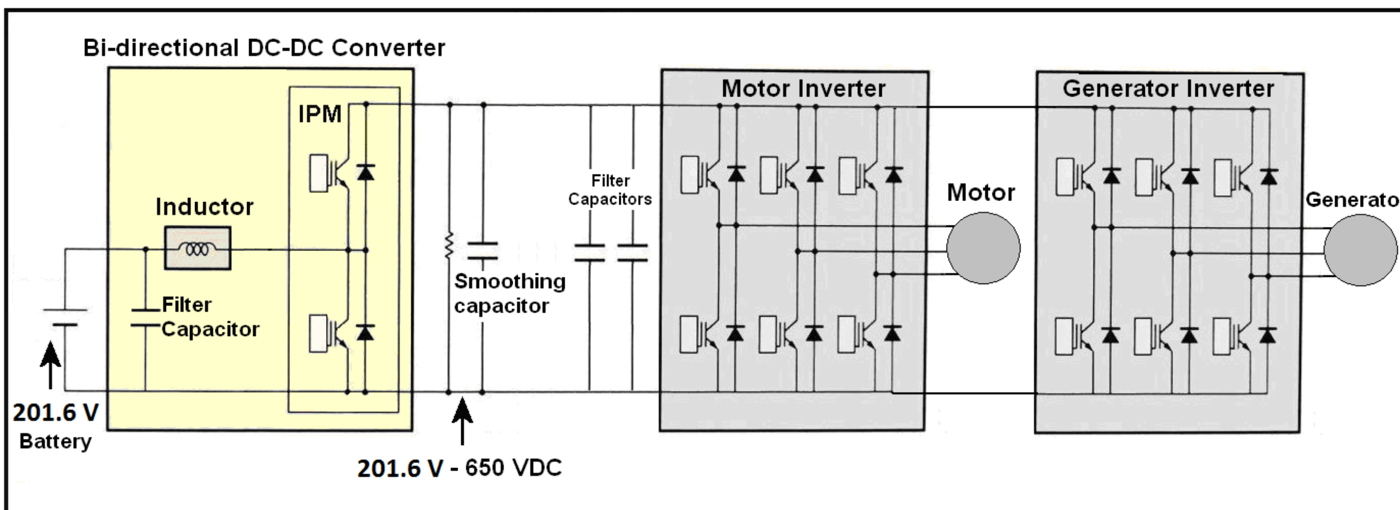
[1] http://energy.gov/sites/prod/files/2014/03/f11/arravt024_ape_poet_2011_p_0.pdf

R&D Focus Area: Wide Bandgap Semiconductors (WBGs)



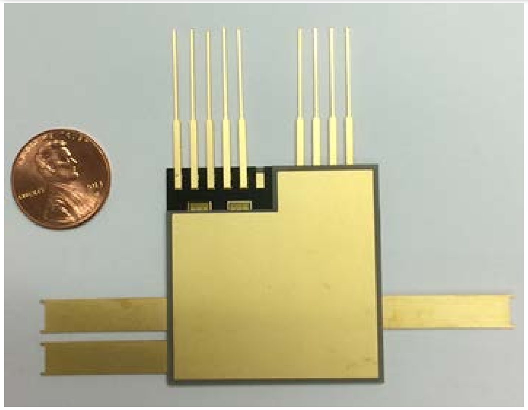


Just 1-2% improvement (halving losses) at inverters and boost could improve roundtrip efficiency 3-6%

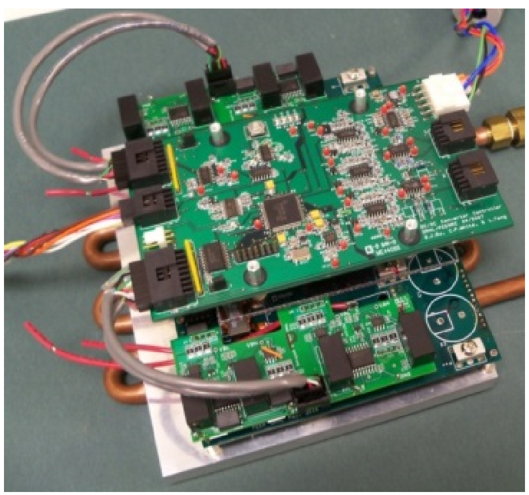


R&D Focus Area: Wide Bandgap Semiconductors (WBGs)

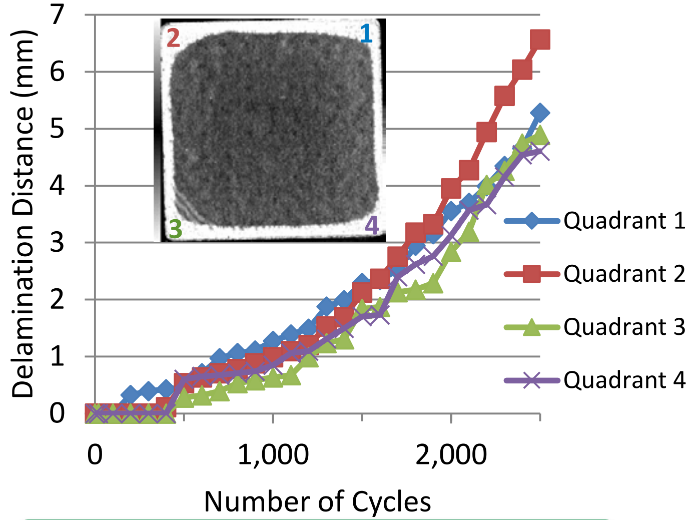
Materials and processes: WBG packaging, capacitors



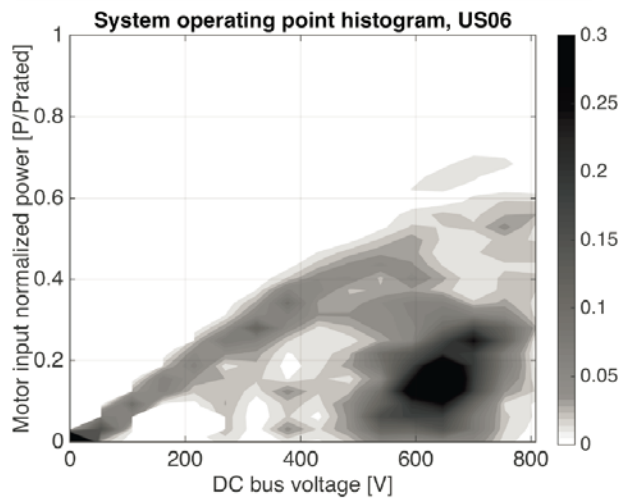
100A/1200V all-SiC Phase-leg Module

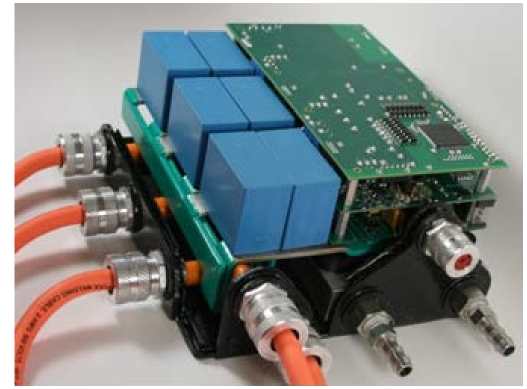


6.6 kW SiC bidirectional converter



System development and simulation for WBG applications

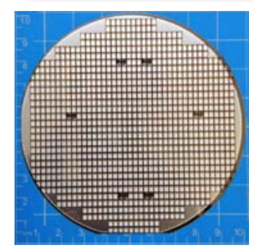




Inverter efficiency at 325V, 1750 RPM, 20 kHz switching

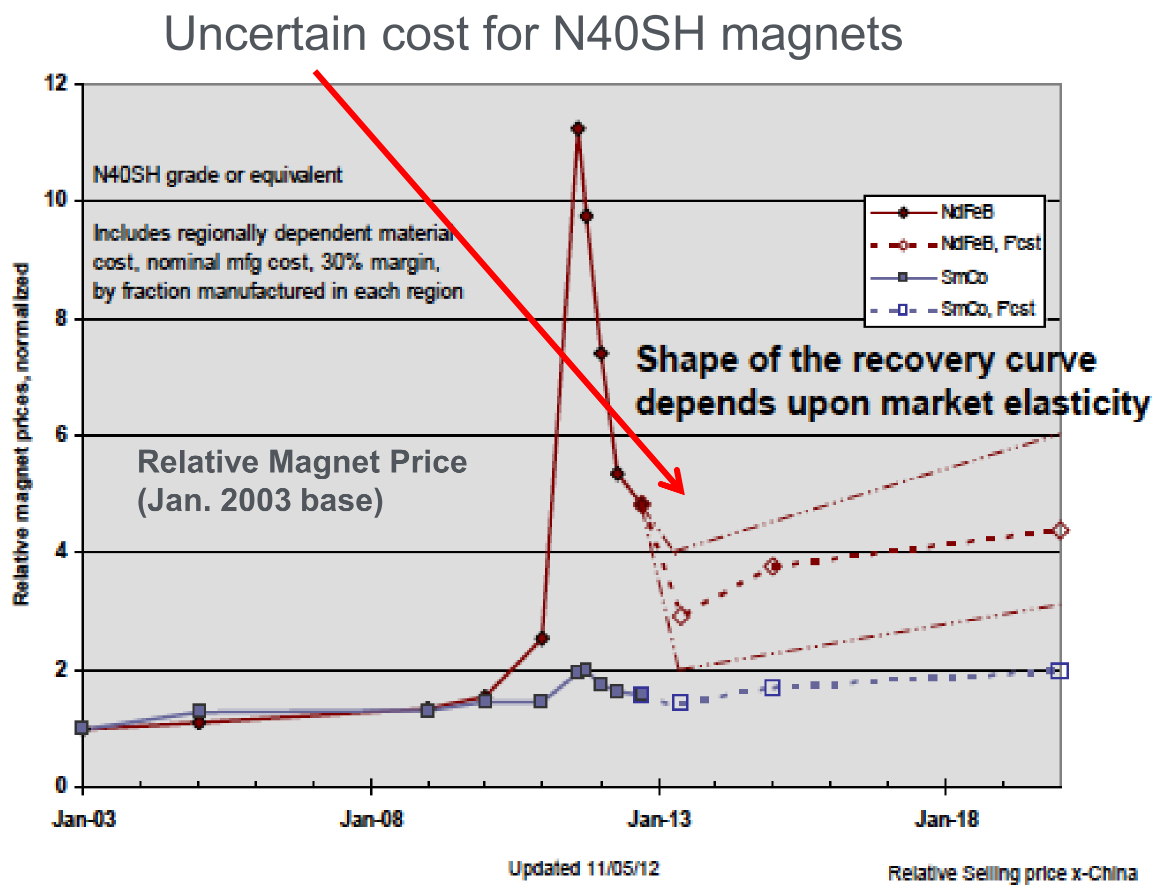
Power (kW)	Efficiency (%)
5	96.4
10	97.8
20	98.5
30	99.2

Component testing and demonstration using WBGs



R&D Focus Area: Non-Rare Earth Motors

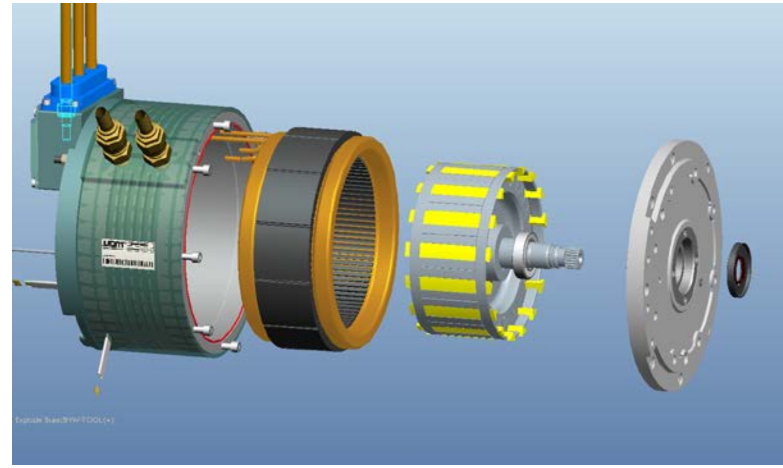
- Currently, the vast majority of electric drive vehicles use Rare Earth (RE) Permanent Magnet (PM) motors due to their high efficiency and power density
- Current RE Neodymium-base PMs need Dysprosium (Dy) to achieve high operating temperatures, and Dy cost can be half of total magnet material cost
- RE elements have increased uncertainty in cost, reduced import quotas, and an eventual looming shortage, especially Dy
- DOE started the Critical Materials Institute to focus on improving the supply, substitutes, use, and forecasting for RE materials, including Neodymium and Dysprosuim
- Many OEMs have recently released new vehicles with motors that use less RE materials, especially Dy



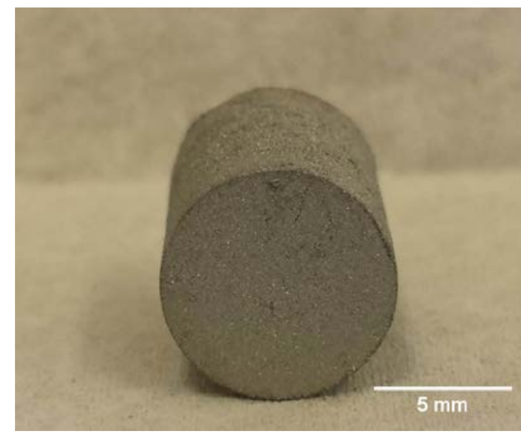
R&D Focus Area: Non-Rare Earth Motors

Research motor design concepts that *reduce* rare earth content

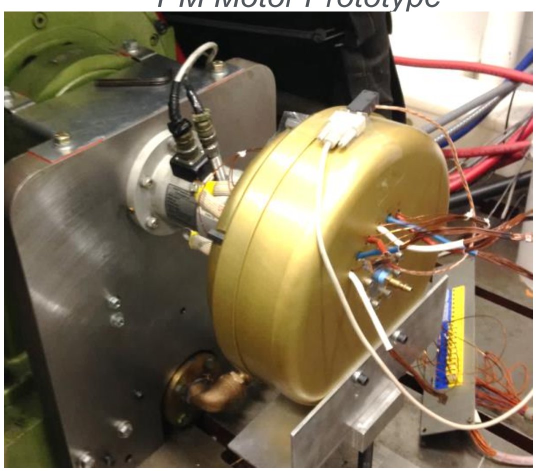
Flux-Switching Dy-Free PM Motor Prototype



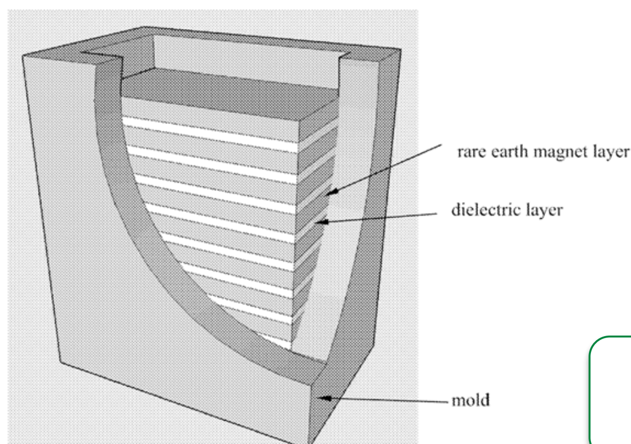
Research motor design concepts that *eliminate* rare-earth magnets – IM, SRM, etc.



Compression molded AlNiCo 8 prototype magnet



Proof-of-Principle Synchronous Reluctance Motor on ORNL Dynamometer



Develop and refine less expensive magnets – AlNiCo or ferrite

EDT Research Leads to Innovations

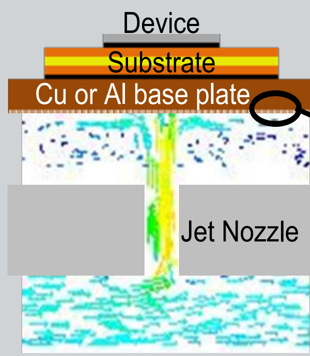
National Laboratory Expertise and Unique Capabilities

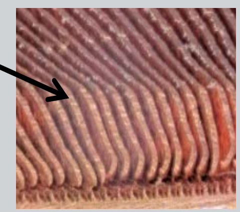
Oak Ridge National Laboratory (ORNL)

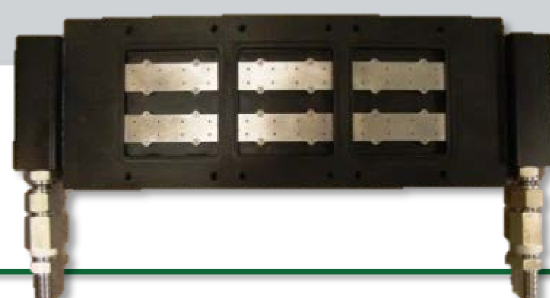
- Power electronics
- Packaging
- Wide Bandgaps (WBG)
- Electric motors

National Renewable Energy Laboratory (NREL)

- Thermal management & reliability

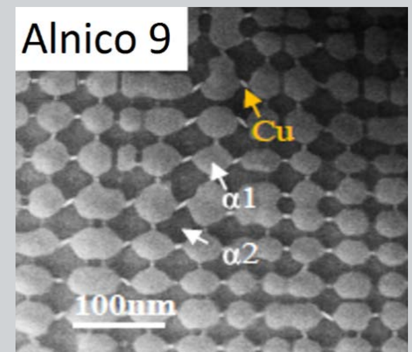


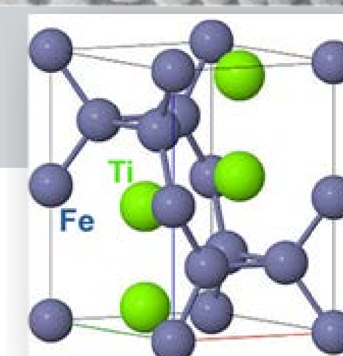




Ames Laboratory

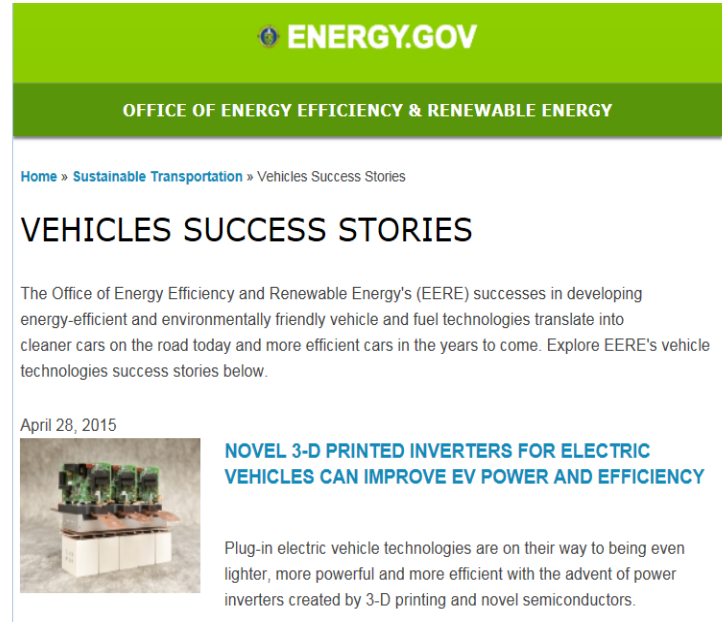
- Magnetic materials





EDT Research Accomplishments

- **Additive Manufacturing Reduces the Size and Weight of Vehicle Power Electronics (ORNL)**
  - *The first-of-its-kind, all-silicon carbide (SiC) traction drive inverter features 50% printed parts and incorporates wide bandgap materials to enable high-temperature operation.*
  - *The inverter was successfully operated at 20 kW with 98.7% efficiency. Its projected power density is expected to surpass DOE EDT technical targets.*
  - *First use of additive manufacturing to accelerate power electronics prototyping.*

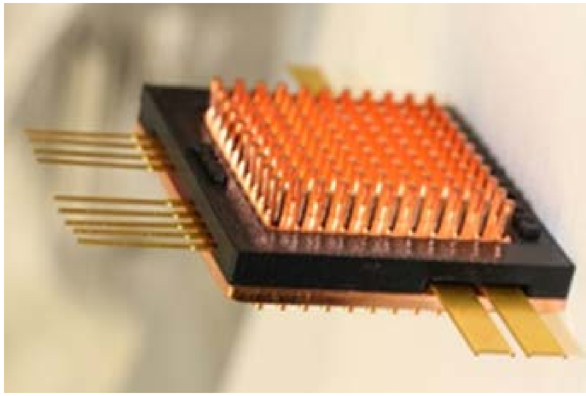


- **Plastic Heat Exchanger Improves Heat Transfer Efficiency and Reduces Inverter Weight (NREL)**
  - *A plastic manifold incorporating jet impingement and surface enhancements increased the heat transfer efficiency by 17% and reduced the traction drive inverter weight by 19%.*


Plastic manifold with jet nozzle inserts

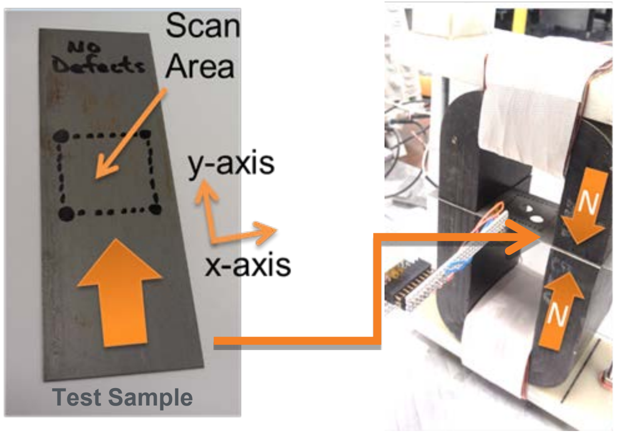
EDT Research Accomplishments

- **Next Generation Wide Bandgap Packaging Improves Inverter Efficiency (ORNL)**
  - *Advanced, 3-dimensional (3D) planar-interconnected all-SiC power module features innovative packaging; offers comprehensive improvements in performance, efficiency, density, and cost of electronic systems.*
  - *SiC 100 A/1,200 V single phase-leg power module using an innovative, planar-bond-all (PBA) packaging technology.*
  - *Latest industrial SiC power devices and a 3D planar interconnection with double-sided direct cooling (both forced air and liquid).*



PBA-SiC power module with 3D planar interconnection and double-sided heat sinks

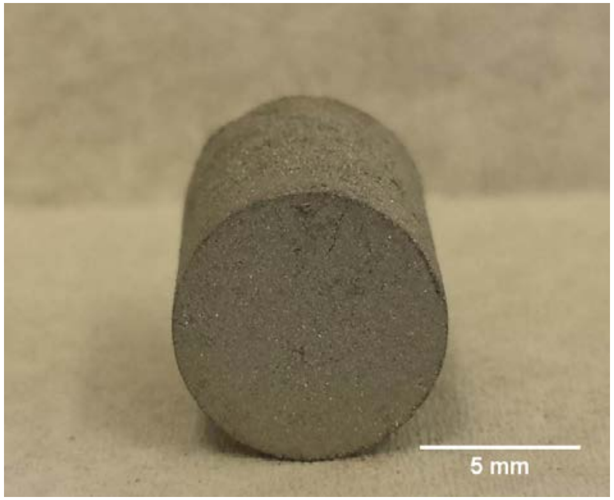
- **New System for Materials Characterization (ORNL)**
  - *Custom characterization system provides a deeper understanding of magnetization and loss mechanisms in electrical steel; provides information needed for high fidelity electric motor modeling.*
  - *Excitation coils can apply a magnetic field to a single sheet sample as the local magnetic field on the surface of the sample is measured.*



Magnetic material test sample (left) and characterization system (right)

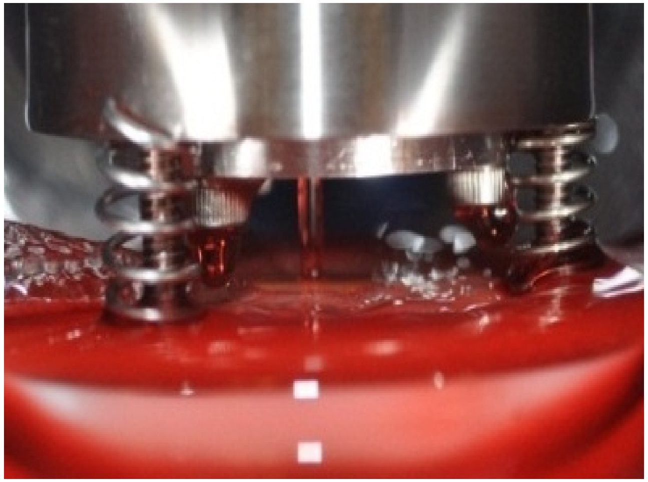
EDT Research Accomplishments

- **Manufacturability of Affordable Non-Rare Earth Magnets (Ames Laboratory)**
  - *Compression molding of gas atomized aluminum–nickel–cobalt (AlNiCo) was identified as the preferred method for producing rare earth free magnets that will reduce the cost of electric traction drive motors.*



Compression molded AlNiCo 8 prototype magnet

- **Motor Thermal Management Enables New Motor Designs (NREL)**
  - *Motor thermal management expertise enabled more accurate measurements of thermal properties related to lamination stacks and automatic transmission oil cooling.*
  - *This effort resulted in first-ever detailed motor component thermal data in the open literature, which will enable motor developers to improve motor models and designs.*



Transmission oil jet impingement on a target surface

EDT Research Innovations Licensed – ORNL Inverter

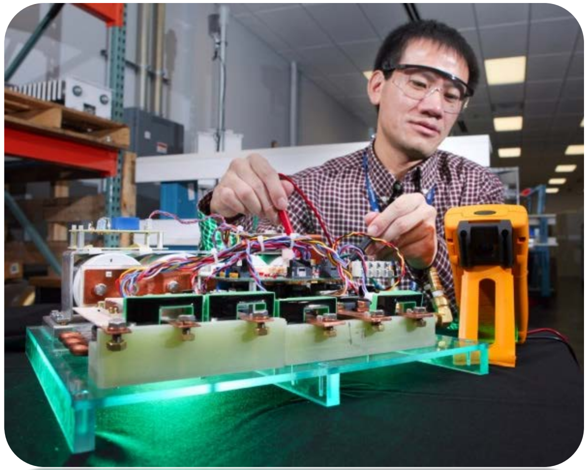
New Hybrid Technologies, LLC, licensed new power conversion technology developed by ORNL. The patented current source inverter* takes direct current voltage and converts it into a multi-phase alternating current for powering electric traction motors.

This technology:

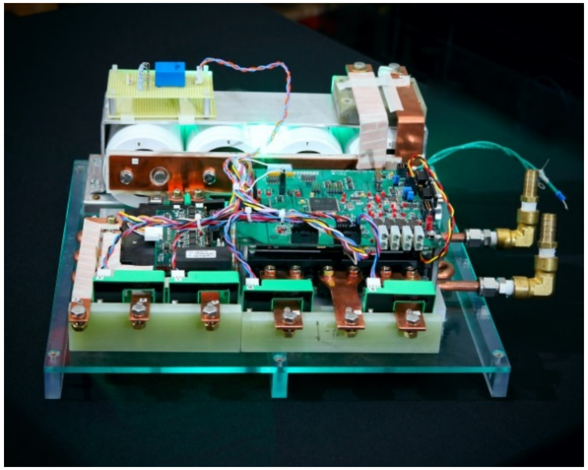
- Increases inverter and motor durability
- Increases motor efficiency
- Increases constant-power speed range in a smaller package
- Enables reduced battery cost and size
- Enables SiC-based current source inverters to operate in elevated temperature environments
- Lowers inverter cost and weight
- Increases vehicle fuel economy

Technology Highlights

- 5X lower total capacitance
- Up to 3.5X higher voltage boost ratio
- 7X to 100X (depending on voltage) lower output voltage total harmonic distortion factor



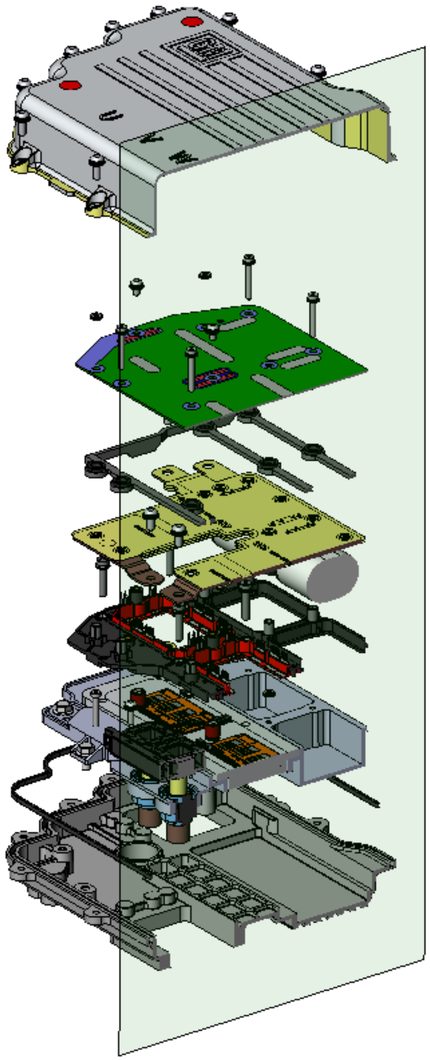
Gui-Jia Su, ORNL Researcher



55 kW current source inverter prototype

*US Pat No. 8,110,948; funded by EDT Research

EDT Development Accomplishments - GM Inverter



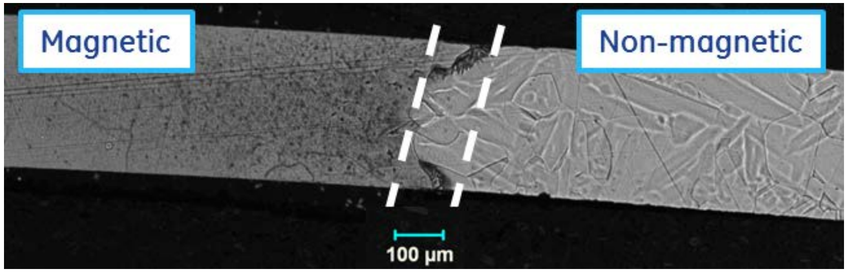
High Power Density

- Manufacturability vs. volume tradeoff: High power density could lead to high cost
- "Next Gen Inverter" pushes for even higher volumetric power density
  - Smaller: Easier to package in vehicle
  - Smaller: Less materials and less expensive
  - Inverter level optimization: All components must be optimized for the chosen inverter architecture
  - Manufacturability must be improved simultaneously

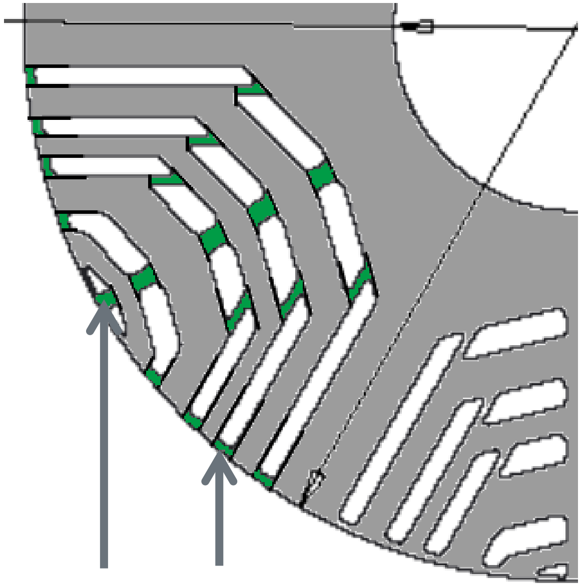
Integrated Power Stage

- Integrated power stage: Eliminate boundaries and empty spaces; new partitioning of functionality
- Vertically integrated process: Power stage manufacturing integrated into inverter assembly
- Manufacturability: Unidirectional (bottom to top) assembly process; reduced assembly steps

EDT Development Accomplishments – GE Motors



Cross section of interface between magnetic and non-magnetic regions



Non-magnetic bridges and posts patterned into magnetic laminate

Alloy and process for producing motor laminates with locally patterned low µ regions have been developed and are being scaled up for prototype demo

Motor accomplishments:

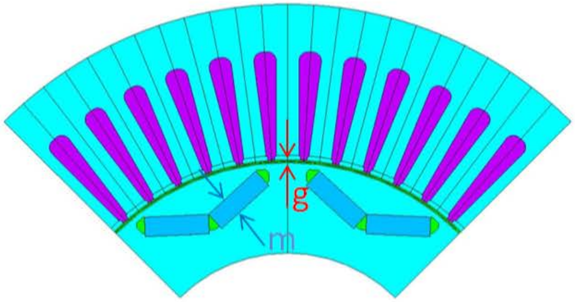
Continue to evaluate more motor topologies (more than 10 evaluated so far)

Down-selected the first 4 topologies: Reduced rare earth (RE) content, non-RE magnets, no magnets, and dual-phase magnetic material

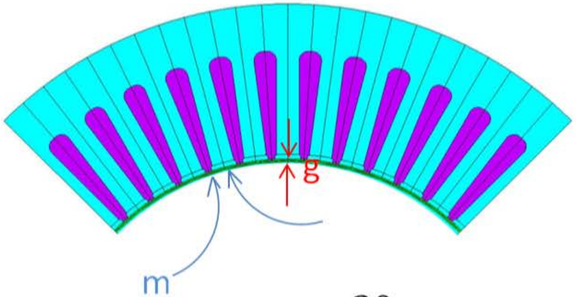
- First prototype has reduced rare-earth content (built and fully tested)
- Second prototype has non-rare earth magnets (built and fully tested)
- Third prototype has no magnets and includes one of the advanced materials (built and currently being tested)
- Fourth prototype is a scaled-down version that includes the dual-phase magnetic material; it is currently being built

Accomplishment: UQM Patents Non-RE Magnet Motor

- UQM recently patented a new design for electric vehicle motors that uses non-rare earth (RE) magnets.
- The new motor design performs comparably to rare-earth motors, and is designed to meet the same goals as permanent magnet-based motors.
- Utilization of AlNiCo magnets will hedge the volatile pricing of NdFeB and other rare earth constituents.
- UQM's project strategy is to use and refine a magnetic circuit that avoids demagnetization: high permeance coefficient and low armature reaction fields experienced at the magnets.



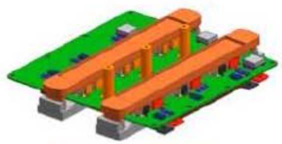
$$P.C. \sim \frac{m}{g} \sim \frac{3}{1}$$



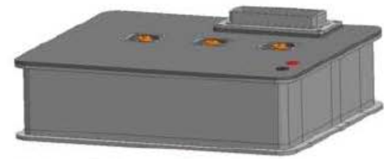
$$P.C. \sim \frac{m}{g} \sim \frac{20}{1}$$

Accomplishment: Delphi Inverter R&D Transitions to Volt

Discrete packaged Silicon Unique to Delphi



Integrated PCB



Advanced Inverter

2008 Start

2013 End

Delphi Project Targets [1]

- Improved packaging provides greater than 30% reduction in thermal resistance junction to coolant vs. commercially available
- Advanced Si devices provide conduction losses ~17% lower than target
- Improved packaging and lower device losses allows for use of less silicon, reducing package size, weight, and improving manufacturability – gives lower cost

Volt Traction Power Inverter Module [2]

"In the second-generation unit, better power flow between the inverters, better efficiency and thermal robustness enabled an average electric drive system FTP city efficiency improvement of 6%, a projected charge sustaining (CS) label fuel economy increase of 10%"

"GM selected Delphi's novel dual-side cooled Viper as the power device for the TPIM. Viper… enabled the reduction of the silicon footprint, allowing for greater layout flexibility and reduced cost."

2016 Volt

[3]

[1] http://energy.gov/sites/prod/files/2014/03/f10/ape012_taylor_2011_o.pdf
[2] http://www.greencarcongress.com/2015/04/20150423-voltec.html
[3] © General Motors

Information Sources

FY 2014 Electric Drive Technologies Annual Progress Report

- http://energy.gov/eere/vehicles/downloads/vehicle-technologies-office-2014-electric-drive-technologies-annual-progress

Electrical and Electronics Technical Team Roadmap

- http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/eett_roadmap_june2013.pdf

EV Everywhere Blueprint

- http://energy.gov/sites/prod/files/2014/02/f8/eveverywhere_blueprint.pdf

Vehicle Technologies Multi-Year Program Plan 2011-2015

- http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf

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http://energy.gov/eere/vehicles/vehicle-technologies-office-power-electronics-and-electrical-machines/