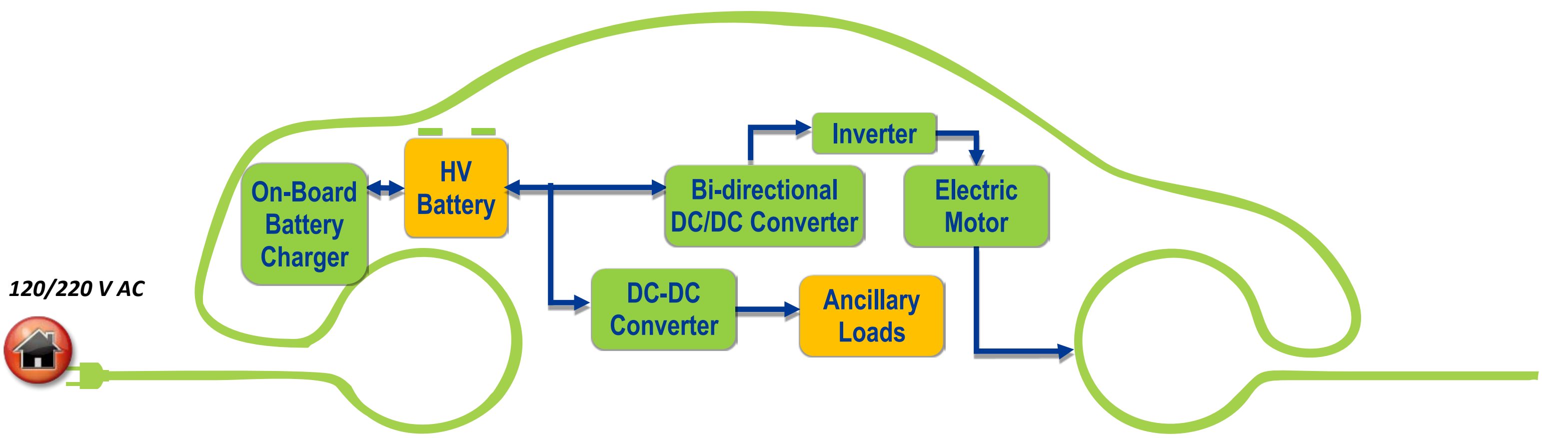
USDRIVE

DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Electrical and Electronics Technical Team Roadmap

June 2013



This roadmap is a document of the U.S. DRIVE Partnership. U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability) is a voluntary, non-binding, and nonlegal partnership among the U.S. Department of Energy; USCAR, representing Chrysler Group LLC, Ford Motor Company, and General Motors; Tesla Motors; five energy companies – BP America, Chevron Corporation, Phillips 66 Company, ExxonMobil Corporation, and Shell Oil Products US; two utilities — Southern California Edison and DTE Energy; and the Electric Power Research Institute (EPRI).

The Electrical and Electronics Technical Team is one of 12 U.S. DRIVE technical teams ("tech teams") whose mission is to accelerate the development of pre-competitive and innovative technologies to enable a full range of efficient and clean advanced light-duty vehicles, as well as related energy infrastructure.

In March 2012, DOE announced a 10-year vision for plug-in electric vehicles (PEVs), called the "EV Everywhere Grand Challenge." EV Everywhere aims to enable American innovators to rapidly develop and commercialize the next generation of technologies to achieve the cost, range, and charging infrastructure necessary for widespread PEV deployment. As demonstrated in its guiding Blueprint document, EV Everywhere aligns with U.S. DRIVE technical areas focused on electrochemical energy storage, electrical and electronics, materials, vehicle systems and analysis, and grid interaction (for more information, please see www.vehicles.energy.gov/electric_vehicles/10_year_goal.html).

For more information about U.S. DRIVE, please see the U.S. DRIVE Partnership Plan, www.vehicles.energy.gov/about/partnerships/usdrive.html or www.uscar.org.

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Mission

The Electrical and Electronics Technical Team's (EETT's) mission is to enable cost-effective, smaller, lighter, and efficient power electronics and electric motors for electric traction drive systems (ETDSs) while maintaining performance of internal combustion engine (ICE)-based vehicles. The EETT also identifies technology gaps, establishes R&D targets, develops a roadmap to achieve technical targets and goals, and evaluates the R&D progress toward meeting the established R&D targets and goals.

This mission directly supports the U.S. DRIVE Partnership mission to accelerate the development of pre-competitive and innovative technologies to enable a full range of efficient and clean advanced light-duty vehicles, as well as related energy infrastructure; specifically the goal below.

> *U.S. DRIVE Partnership Goal (1): Enable reliable hybrid electric, plug-in hybrid and range-extended electric, and battery electric vehicles with performance, safety, and costs comparable to or better than advanced conventional vehicle technologies, supported by charging technologies that can enable the widespread availability of electric charging infrastructure.*
>
> *2020 Partnership Research Target: An electric traction drive system at a cost of $8/kW.*

Scope

The EETT focuses on the development of economically viable ETDSs, which include the electric motor, the inverter, and may include a bi-directional DC/DC converter. The team is also responsible for other parts of the power electronics, which may include a voltage step-down (buck) DC/DC converter and an on-board battery charger.

The blue and green boxes shown in Figure 1 below illustrate the components within the EETT's scope.

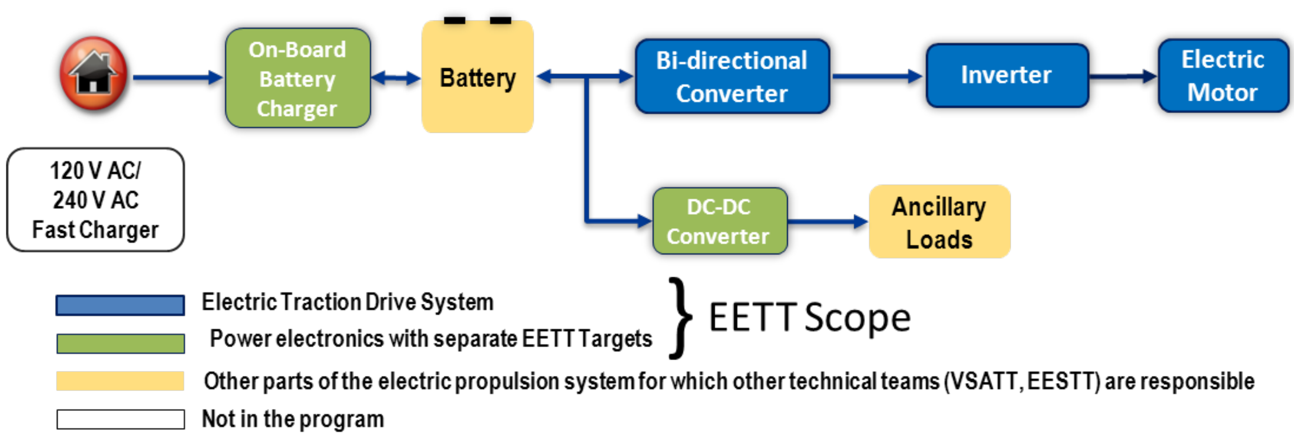

Figure 1. Components of Generic ETDS

The physical delineation for the scope of the EETT ETDS is the DC Bus on the input side of the bi-directional converter and the motor shaft on the output side. The on-board battery charger is slightly different where the input boundary is the external AC electrical interface for the input and the DC Bus to the battery on the output. Since everything beyond those interfaces is outside the scope of the EETT, the team must work with other tech teams and groups such as the Grid Interaction Tech Team (GITT), Vehicle Systems Analysis Tech Team (VSATT), and Electrochemical Energy Storage Tech Team (EESTT) to coordinate efforts and research goals. This coordination enables the development of research goals that are reasonable and balanced and ensures one system is not optimized at the expense of an interfacing system. Examples of interfacing systems are the electric vehicle supply equipment (EVSE), the high voltage battery and the gearbox (or transmission). Likewise, research goals must also consider the vehicle constraints related to electromagnetic compatibility (EMC) and noise, vibration and harshness (NVH).

The emphasis of the EETT Roadmap is on increased vehicle electrification. Ideally, each new and innovative technology will be scalable and can be applied to the major components in vehicles with various degrees of electrification. These major components can be applied to various vehicle types as illustrated in Table 1 below.

Table 1. Important Features of Various Types of Vehicles

Key	++ Critical		+ Desirable	
ETDS Key Parameters	**Vehicle Types**			
	ISG-Type HEV	**HEV and Blended PHEV**	**PHEV and EREV**	**EV (BEV or FCV)**
ETDS Usage	Limited or no electric traction. Utilizes non-hybrid trans.	Hybrid 2-motor transmission. Multiple modes of operation for each motor through transmissions, clutches, and planetary gear sets. Variable gear ratios.	EREV Motor A – generator to charge battery; Motor B – full range electric traction.	Full speed range electric traction. Fixed gear ratio.
Number of Electric Motors and PIMs Required	1	2, traction and generator	2, traction and generator	1
Peak Mechanical Output Power (kW)	10-40	85 (traction) 60 (generator)	70-110 (traction) 45-55 (generator)	110-150
Continuous Mechanical Output Power (kW)	6-14	20-30 (traction) 20-30 (generator)	35-85 (traction) 20-40 (generator)	65
High Torque Density and Power Density (Volume)	++	++ (package in hybrid transmission)	+	+
Weight	++	+	++	++
ETDS Wide High-Efficiency Area Around Maximum Continuous Power	+	+	++	++
ETDS High Efficiency @ Maximum Peak Power Levels	+	+	++	++
ETDS Efficiency over Wide Input Voltage Ranges	++	+ (narrower voltage range)	+ (depends on battery control strategy)	++
Motor Cooling – Current Options	Ethylene Glycol water jacket	Transmission Oil Spray	Transmission Oil Spray	Ethylene Glycol Water Jacket or Transmission Oil Spray
Inverter Cooling – Current Options	Ethylene Glycol	Ethylene Glycol (High temp loop 105°C or low temp loop 75°C)	Ethylene Glycol (High temp loop 105°C or low temp loop 75°C)	Ethylene Glycol (Low temp loop 75°C)
Inverter Ambient Air Environment	-40°C to 105°C (remote) -40°C to 125°C (on trans)	-40°C to 105°C (remote) -40°C to 125°C (on trans)	-40°C to 105°C (remote) -40°C to 125°C (on trans)	-40°C to 85°C
Difficulty of Integration	High	High	Medium High	Medium High
Cost (relative to overall system)	++	++	+	+

Key Issues and Challenges

Key Issues

To achieve the vision for the ETDS, a number of key issues must be overcome which include:

- *Cost*. The components added for electrification must become more affordable. The additional content which includes the motor, inverter, converter, and on-board charger must be offset by the cost savings in operational costs as seen by the customer over a three year period.
- *Small and compact*. Significant reductions in the volume and weight of components will allow for ease of integration within current vehicle architectures.
- *Efficient*. The efficiency of the components must continue to improve to provide value to the customer (e.g. displayed in longer EV range, higher MPG and/or MPGe ratings).
- *Reliable*. The ETDS must be reliable and provide long vehicle service equal to or better than conventional petroleum powered vehicles.

Challenges

Many challenges exist including technical, market, environmental and domestic supply availability.

- *Technical*. From a technical perspective, significant technical advances are required to achieve the necessary cost reductions. Even as volumes increase and the production volumes grow, further cost reductions will still be needed. To better understand this, empirical cost data collected from numerous industries have shown that unit costs of developing technologies typically follow a curve such as the ones shown in Figure 2. The curves relate unit costs to cumulative production volume and are defined by cost entry points and progress ratios. A progress ratio of 90% describes a product or technology that experiences a 10% reduction in cost for every doubling of cumulative production. Studies have shown that progress ratios for repetitive electronics manufacturing are typically 90% to 95% with similar rates for repetitive machining operations.[1,2]

  The existing traction-drive cost estimates in Figure 2 were derived from three cost assessments conducted on the Gen I Toyota Prius,[3] the Gen II Toyota Prius, and the MY2007 Toyota Camry.[4] The projected progress ratio for these data points is approximately 97% (or 3% cost reduction for every doubling of cumulative production), a lower rate of cost reduction compared to the referenced values. While there is some uncertainty of the exact progress ratio, the ultimate cost target of $8/kW for the ETDS that yields consumer value for electric traction based vehicles will not likely be reached through production volume alone or incremental technology advances. Substantial investment in R&D is typically required to achieve the type of technology breakthroughs needed to reach cost targets.

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1 Delionback, L.M. “Learning Curves and Progress Functions,” Chapter 5. Stewart, R. et al., ed. *Cost Estimators Reference Manual.* John Wiley and Sons, 1995.

2 *Experience Curves for Energy Technology Policy.,* International Energy Agency 2000, online http://iea.org/textbase/nppdf/free/2000/curve2000.pdf.

3 Energy and Environmental Associates, *Technology and Cost of MY 2004 Toyota Prius*, ORNL/TM-2013/175, 2006.

4 Energy and Environmental Associates, *Technology and Cost of MY 2007 Toyota Camry HEV*, ORNL/TM-2007/132, 2007.

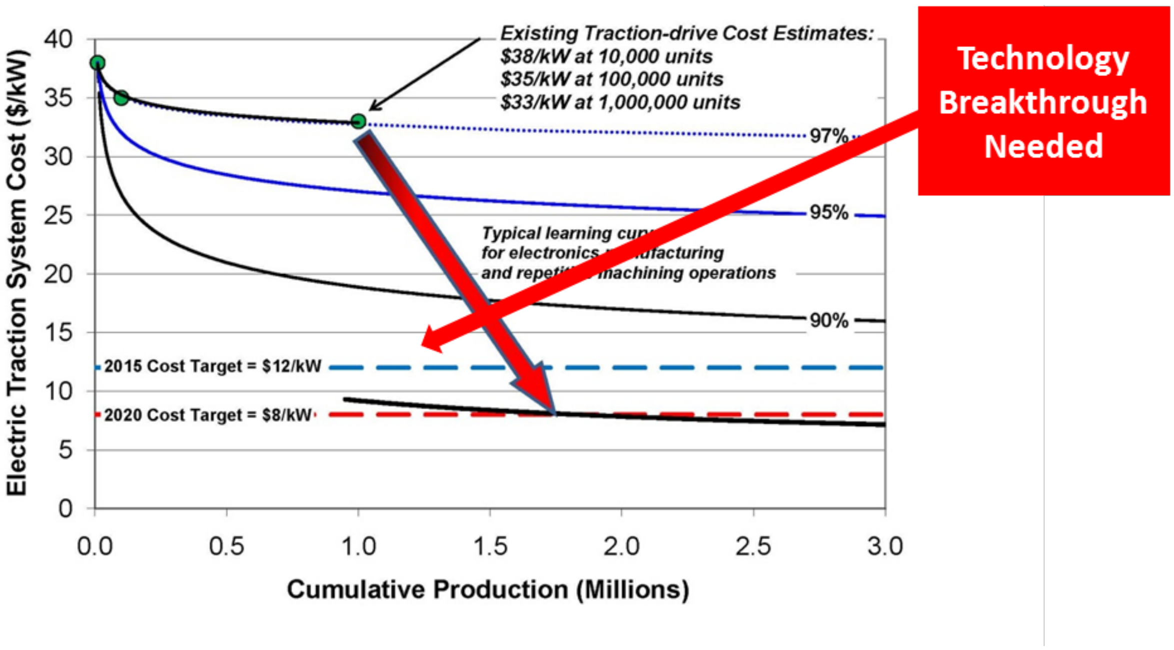


Figure 2. Required Technology Shift to Achieve Cost Target for ETDS

- *Market*. From a technical viewpoint, the preferred motor for an ETDS, based on efficiency and power density considerations, is an interior permanent magnet (IPM) motor with rare earth magnets. Until other sources of rare earth metals are developed, China will have a virtual monopoly on those materials. That monopoly on the supply of rare earth metals can induce market price fluctuations that can have a significant impact on today's cost of an electric motor. A few years ago, the price of sintered, rare earth magnets was decreasing. Starting in 2009, the price increased significantly and then decreased, but the price did not return to the 2009 price. For example, Figures 3 and 4 show how drastically the price of neodymium and of dysprosium have fluctuated. As of April 2013, the price neodymium was $90/per kg outside of China and $63.25/per kg within China. The price of dysprosium was $775/per kg outside of China and $522/per kg within China. Due to this price volatility, alternative materials and motor technology will need to be investigated.
- *Environmental*. Successful integration of power electronics and electric motors into an ETDS requires achieving various thermal characteristics and performance targets while reducing the cost, volume, and weight of power electronic components. Components must be durable and able to function reliably at high operating temperatures and in adverse conditions that include vibrations, dirt, and humidity over the life of the vehicle. Those components must also be robust to the EMC requirements for the vehicle and also must have acceptable NVH characteristics.
- *Domestic supply availability*. The development of the domestic supply base is important to having regional availability for the U.S. market and encourages greater innovation between OEM and supplier. Performing R&D for ETDSs require a mechanism so that the technology can be transferred to the industry's supply base. Because this effort is so closely aligned to industry application, it is conducted via cost-shared contracts with industrial teams consisting of OEMs and suppliers. The lessons learned in these efforts supply feedback to the module development efforts conducted by suppliers working with the national laboratories. This assists in developing a supply chain that is responsive to auto manufacturer needs. Some key features related to manufacturing and vehicle integration are important:

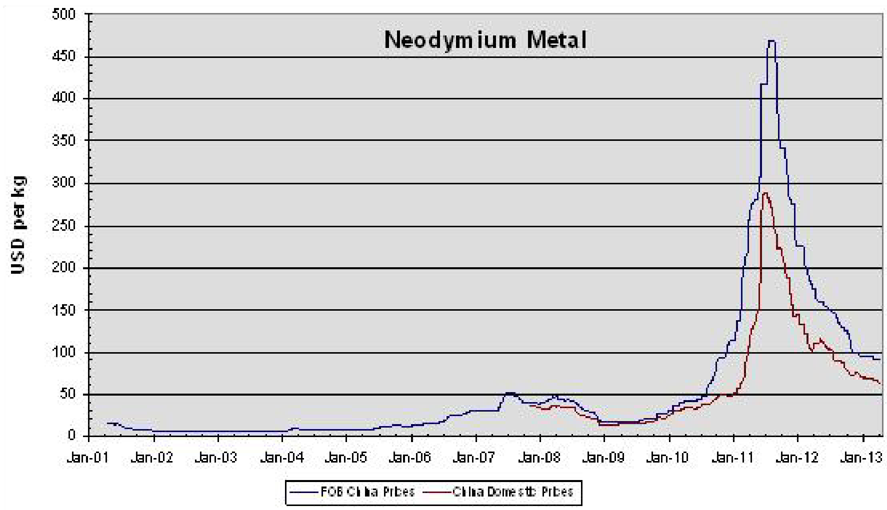


Figure 3. Annual Price Trend for Neodymium Metal[5]

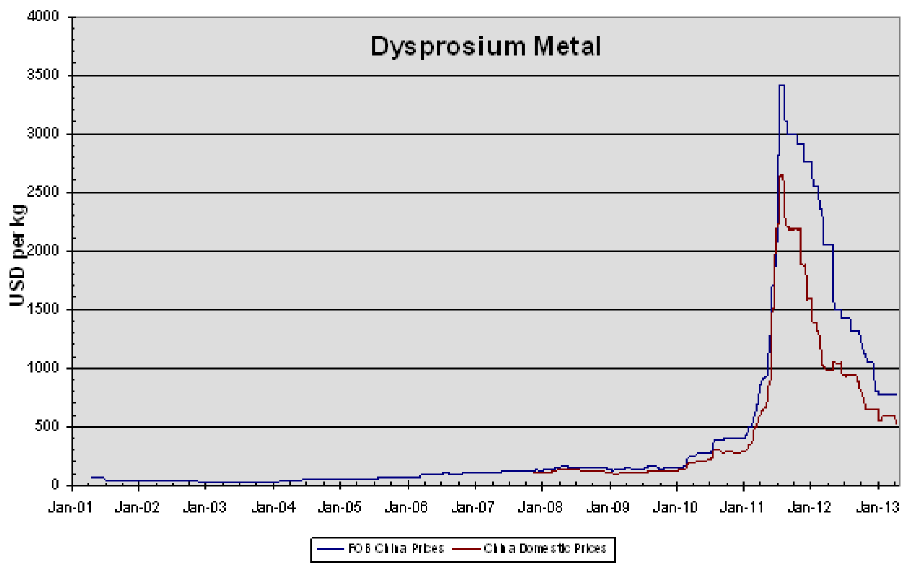


Figure 4. Annual Price Trend for Dysprosium Metal[5]

– *Scalable and flexible*. Designing components with standardized dimensions will facilitate easy assembly, repair, and flexibility in arrangement.
– *Affordable*. The ability to interchange parts among manufacturers' vehicle models, as well as among manufacturers, will create a greater range of applications for each component. The supplier base will grow as demand for components grows, subsequently leading to large-scale production and lower per-unit production costs.

[5] Arnold Magnetics, *The Erratic by Continuing Demand for Rare Earth Materials in Permanent Magnets*, presentation at the Beyond Rare Earth Materials (BREM) VII Workshop, Ames Laboratory, Ames, Iowa, October 2012.

- *Easy to manufacture*. In order to assure multiple sources of components, the component design should be simple enough to allow for its manufacture by several suppliers.
- *Easy to install*. Reduce vehicle assembly complexity.

Technical Targets and Current Status

Target Definition

The long-term (2020) technical targets for the ETDS are based upon what is needed for an HEV, BEV, PHEV, or FCV to be competitive in performance and economics. Achieving these aggressive targets will require major technological breakthroughs. The ability to package power electronics and electric motors across the range of vehicle types is essential to achieving scale of production and program objectives of reducing U.S. energy consumption. The metrics established by the EETT are focused on the key issues related to the cost, size, weight, and efficiency of the components to enable wide spread acceptance of these vehicles. Three of those metrics are normalized into cost/kW, power density, and specific power.

Cost

Ultimately, hybrid and electric-drive vehicles should cost no more than comparable ICE vehicles. The cost targets allow for a small price premium, but the cost difference should be no greater than that which could be recovered from the fuel savings in 3 years. The cost targets to satisfy those requirements were established by the Tech Team experts and set as $12kW in 2015 and $8/kW in 2020.

While the cost targets were developed for an HEV application, consideration was given to other applications. For FCVs, the cost target is similar to that established above for HEVs and depends upon success in fuel cell stacks and hydrogen storage meeting cost targets. For PHEV applications, the allowable PEEM cost is the same as for the HEV.

Power Density

Power density is an extremely important target because of limited space "under the hood" and in the vehicle. Packaging constraints vary with the different types of electric drive applications (see Table 1) but can be of greatest concern in vehicle types that have the most potential for reducing the U.S. vehicle fleets fuel usage.

Specific Power

Mass directly affects overall fuel efficiency, and the benefits of the additional ETDS can be greatly reduced if the mass is not carefully managed. Additionally, increasing vehicle mass complicates and may even prevent integrating ETDSs into vehicles.

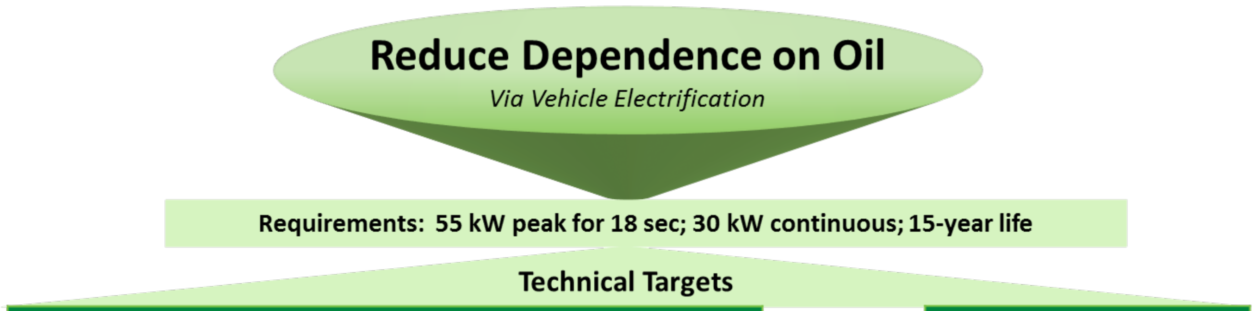
Efficiency

System efficiency is important, not only for the direct effect on fuel consumption, but equally important is that the losses (inefficiencies) are converted to heat, which must be removed with a thermal management system that carries added cost, weight, volume, and system complexity.

EETT Targets

Electric Traction Drive System Targets

The technical targets for 2015 and 2020 that are shown in Figure 5 are appropriate for an HEV application. For other applications, the targets may be adjusted on a case-by-case basis. Selecting the HEV application, which has a power level near the low end of the range (representative for a light-weight, mid-size sedan), is appropriate for this program because that is where the challenge of meeting the specific power and power density targets would be greatest. Meeting the targets for more powerful systems should be somewhat easier because some of the "overhead" items (e.g., connectors) would not have to be entirely proportional to the power.



Electric Traction Drive Systems (ETDS)

Impact	Reduce Cost	Reduce Weight	Reduce Volume	Reduce Energy Storage Requirements
Year	**Cost ($/kW)**	**Specific Power (kW/kg)**	**Power Density (kW/l)**	**Efficiency (%)**
2015	12	1.2	3.5	>93
2020	8	1.4	4.0	>94

Power Electronics (PE)

($/kW)	(kW/kg)	(kW/l)
5	12	12
3.3	14.1	13.4

Electric Motors (EM)

($/kW)	(kW/kg)	(kW/l)
7	1.3	5
4.7	1.6	5.7

Figure 5. Technical Targets for the ETDS

Electric Motor Targets
Although the technical targets have been established at the system level, an approximate allocation of the targets between the motor and the power electronics is useful as guidance for projects that address one or the other. The values in Figure 5 estimate how much can be achieved with improvements to the motor and, along with comparable numbers for the power electronics, are consistent with the system-level targets.
Important to note is that certain motor designs may have an impact on the weight, volume, and cost of other parts of the vehicle. Although many vehicle architectures require two electrical machines, one as a motor and another as a generator, some architectures make use of a single machine for both purposes. The targets in Table 5 refer to one machine.

Inverter Targets
An approximate allocation of the targets for the power electronics is shown in Figure 5. The values estimate how much can be achieved with improvements to the power electronics and are consistent with the system-level targets.

DC/DC Converter Targets
In addition to running accessories from the high-voltage bus, HEVs, PHEVs, BEVs and FCVs also will require up to 3 kW of 14 V DC; the power level will depend upon the vehicle architecture and the features content. At a minimum, a buck DC/DC converter will be required to reduce the nominal 325 V battery voltage to 14 V for the accessories. Although not a part of the propulsion system, a DC/DC converter is an important power electronics module and, therefore, is included in the scope of this program. In addition, some of the technical developments for DC/DC converters may be transferable to inverter designs. Table 2 shows technical targets, as established by the OEMs, for a 3 kW DC/DC converter to

reduce the battery or fuel cell voltage from a nominal input voltage of 325 VDC to 14 V. The cost target for 2020 is such that it will cost no more than the alternator that it replaces.

Table 2. Technical Targets for 3 kW DC/DC Converter

	2015	2020
Cost, $/kW	<60	<50
Specific power, kW/kg	>1.0	>1.2
Power density, kW/L	>2.0	>3.0
Efficiency	>93%	>94%

Charger Targets
Technical targets for the charger will be determined in consultation with the other Tech Teams.

R&D Status

The R&D portfolio is focused on technology development rather than system development. Thus, complete ETDSs for a specific application have not been produced by the program. System attributes, however, can be estimated by conceptually "building" ETDSs using the technology advances from the R&D effort.

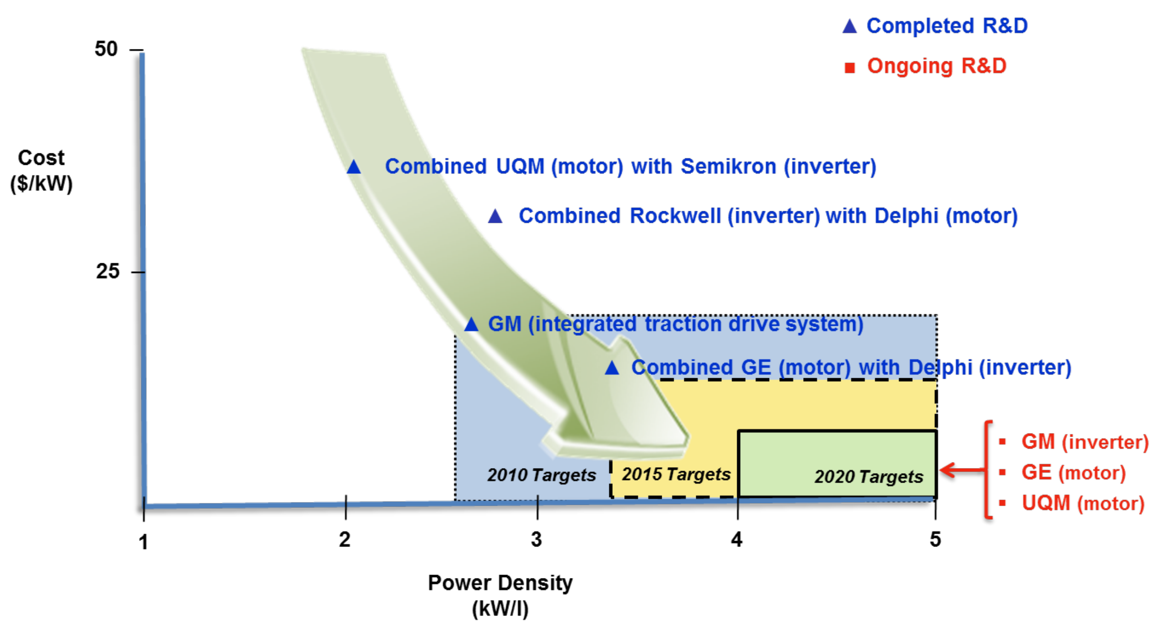


Figure 6. R&D Progress versus Targets

Figure 6 depicts the R&D progress that has been made in recent years with cost and power density improvements for motors, inverters, and traction drive systems. Future implementation of recently available high-temperature power switches, capacitors, and other innovative power electronics and motor materials as well as new design strategies will permit researchers to reduce or eliminate cooling system requirements, thus obtaining the 2020 R&D targets for cost and weight improvements.

Gaps and Technical Barriers

Gaps

Production hybrid technology will be used to represent the status of on-the-road technology. As indicated, significant gains have been made in volume and weight as the technology has advanced. However, these gains have been at the expense of cost and efficiency.

Table 3. Status of On-the-Road Technology for ETDS

	Cost (\$/kW)	Specific Power (kW/kg)	Power Density (kW/L)	Efficiency[a] (%)
MY2004 Prius[6]	35	0.9	1.7	82
MY2007 Camry[7]	34	1.2	3.3	83
MY2008 Lexus[8]	54	1.9	4.1	81
MY2010 Prius[9]	34.9	1.3	2.6	85
2015 Target	12	1.2	3.5	93
2020 Target	8	1.4	4.0	94

[a.] Efficiency is specified @10% rated speed @20% rated torque.

The on-the-road technology status presented in Table 3 was used to identify the gaps that must be bridged to meet the program targets. It should be noted that the Lexus system is a high-power traction drive system on a vehicle that is performance oriented rather than fuel-economy oriented. Given the base cost of the Lexus (MSRP greater than $100K), the price premium associated with the hybrid drive system was most likely not a primary consideration in the design space. The cost for the MY2004 Prius model was obtained at a time when rare earth material was fairly low cost, while the cost for the MY2010 Prius model was obtained when the cost of permanent magnets was high.

The performance information contained in Table 3 comes directly from benchmarking results obtained by the program operating the on-the-road technology as it was designed to be used in the vehicle. The cost estimates were derived from technology assessments performed for the program and dealer cost information.

[6] ORNL, *Evaluation of 2004 Toyota Prius Hybrid Electric Drive System*, ORNL/TM-2006/423, 2006.
[7] ORNL, *Evaluation of 2007 Toyota Camry Hybrid Synergy Drive System*, ORNL/TM-2007/190, 2008.
[8] ORNL, *Evaluation of 2008 Toyota Lexus LS 600H Hybrid Electric Drive System*, ORNL/TM-2008/185, 2009.
[9] ORNL, *Evaluation of 2010 Toyota Prius Hybrid Synergy Drive System*, ORNL/TM-2010/253, 2011.

Technical Barriers

The major technical barriers to closing the gaps between the current status and the targets are the high cost of the materials and components, the large volume needed to package these components, additional weight of the components, and high component losses that leads to large thermal management systems which add cost, volume and weight.

Cost of Materials and Components

To reduce the cost of the ETDS, the initial focus obviously should be on the most costly components.

The relative contributions to the cost of a PM motor have changed significantly within the past few years with the increased costs of rare-earth magnets. Although the exact costs would depend upon the specific design, an example of approximate cost contributions for a typical IPM motor is shown in Table 4.

Table 4. Approximate Contributions to Material Cost of Motor
(Typical IPM[10])

Sintered neodymium boron magnets	53%
Housing	18%
Copper	10%
Miscellaneous (shaft, bearing, etc.)	10%
Laminations	9%

Cost elements for an inverter vary widely depending upon the specific topology. Major components with projected cost elements for a high-performance inverter unit are listed in Table 5.

[10] Based on ORNL Benchmark Data of 2012 Nissan LEAF (publication pending fall 2013).

Table 5. Projected Future Power Inverter Cost Drivers to 2016[11]

PCB Assemblies/Components	25%
Power Silicon	25%
Thermal Management	16%
Capacitors	11%
Connectors	8%
Housing/Structures	5%
Microprocessors	4%
Current Sensors	3%
Miscellaneous	3%

Component Volume and Efficiency

Reduction in the package volume of the components is necessary to enable packaging of these systems into the increasingly smaller spaces available within the vehicle. The motor volume reduction is limited by the flux density capabilities represented in the materials used in current electric steels and the electrical conductivity limitations of copper windings. Until new material advances can be made to improve these characteristics, the obvious method to reduce volume is to increase motor speeds as discussed in more detail in the next section.

The power electronics volume is driven by the size of the passive components (capacitors and inductors) and the thermal management necessary to keep the electronic components, such as the power modules, sufficiently cool during the demanding environmental conditions of an automotive environment. Proper thermal management of the power electronics is key to ensuring reliable and long life operation. Two focus areas within the inverter are the DC bus capacitor which can occupy up to 40% of the volume and the power module, with its heatsink and cooling structure, which also occupies a significant portion of the total volume.

The efficiency improvement in components is an important characteristic that is synergistic in many areas. With improvements in efficiency, the thermal management system can be reduced leading to overall reductions in volume and weight and cost.

Component Weight

Weight reduction is essential because fuel efficiency is inversely proportional to weight. As Table 6 shows the heaviest parts of an IPM motor are the stator core and rotor core.

[11] Synthesis Partners, LLC, *Technology and Market Intelligence: Hybrid Vehicle Power Inverters Cost Analysis*, report to DOE, July 2011.

Table 6. Approximate Contributions to Motor Weight
(Typical IPM[12])

Stator core	27%
Rotor core	18%
Copper windings	10%
Shaft & bearings	8%
Magnets	3%

PM motors have high specific power relative to other motor designs, and one way to reduce the weight would be to use a higher-speed motor. Since power of a motor is directly proportional to the speed, increasing the speed, in principle, is an obvious way to increase power density. Currently, maximum speeds are in the range of 16,000 to 20,000 rpm; still higher speeds may be impractical for a number of reasons:

- Resulting high centrifugal forces will make it difficult to retain the magnets in IPM designs
- Increased core losses at high speed will reduce efficiency
- Traditional gears and bearings may not be able to tolerate the higher speeds
- Additional requirements on the mechanical components to enable high speed operation of the gear box may offset the motor savings.

The heaviest parts of an inverter are shown in Table 7.

Table 7. Approximate Contributions to Inverter Weight
(Based on 2012 Nissan LEAF[13])

Heat exchanger	37%
Power modules, gate drivers, PWBs	23%
Housing	15%
Capacitors	12%
Bus bars	7%
Current sensors	6%

[12] Based on ORNL Benchmark Data of 2012 Nissan LEAF (publication pending fall 2013).
[13] Based on ORNL Benchmark Data of 2012 Nissan LEAF (publication pending fall 2013).

Strategy to Overcome Barriers and Achieve Technical Targets

Achieving long-term future oil savings in highway vehicles is directly tied to successful market penetration of advanced electric drive vehicles. Successful market penetration requires consumer acceptance of advanced electric drive vehicles in terms of the following attributes:[14]

- Vehicle price
- Fuel economy
- Range
- Maintenance cost
- Acceleration
- Top speed
- Passenger and luggage space.

Of these, vehicle price and fuel economy are the most important. The cost goal in particular is important since the addition of power electronics, traction motor(s) and controls to the gasoline or fuel cell power plant adds several thousand dollars to the cost. As a result of these additional components, electric vehicle cost (and price) will continue to exceed that of conventional vehicles. A principal objective of the R&D is to reduce component and subsystem cost, so that the additional vehicle cost is recoverable in three years through fuel savings.

Important elements of the strategy:

- **Develop technologies, not vehicles.** The intent of the program, in support of the U.S. DRIVE Partnership, is not to design or build a vehicle but rather to develop a set of technologies that can be adopted (and modified, if necessary) by the OEMs and their suppliers to enable the manufacture of a PEEM system that meets the program goals.
- **Explore multiple technologies.** Since different manufacturers will have different requirements and design strategies, and no single new technology will enable achievement of all of the targets, the program must deal with a wide variety of technologies. Clearly, improvements must be made to both the motor and the power electronics. For the motor, it is necessary to consider issues such as new designs, magnet materials, and manufacturing methods. For the power electronics, it is necessary to consider semiconductor switches, capacitors, magnetics, packaging, and new topologies. Added to all of those issues is the challenge of controlling the temperature of the system components.
- **Pursue parallel paths.** To meet the very challenging technical targets, high-risk concepts must be pursued. To reduce the overall risk of technical failure, it therefore is necessary to pursue more than one path toward each objective. Multiple parallel paths also are more likely to produce technologies that meet the needs of more than one manufacturer.
- **Ensure technology transfer.** New technologies will not have an effect on fuel consumption until they are incorporated into commercial vehicles. Projects must consider balancing the need for long-term, high-risk R&D with short-term R&D to develop technologies to the point where industry can adopt them. In many cases, this shorter-term R&D can be conducted in partnership with industry or by industry alone.

Research Focus Areas

Four research focus areas for the ETDS have been established and are illustrated in Figure 7.

[14] Norland, D., T. Jenkin, *Projected Benefits of Federal Energy Efficiency and Renewable Energy Programs, Appendix J – GPRA06 Vehicle Technologies Program,* NREL/TP-620-37931, National Renewable Energy Laboratory, Golden, CO, May 2005.

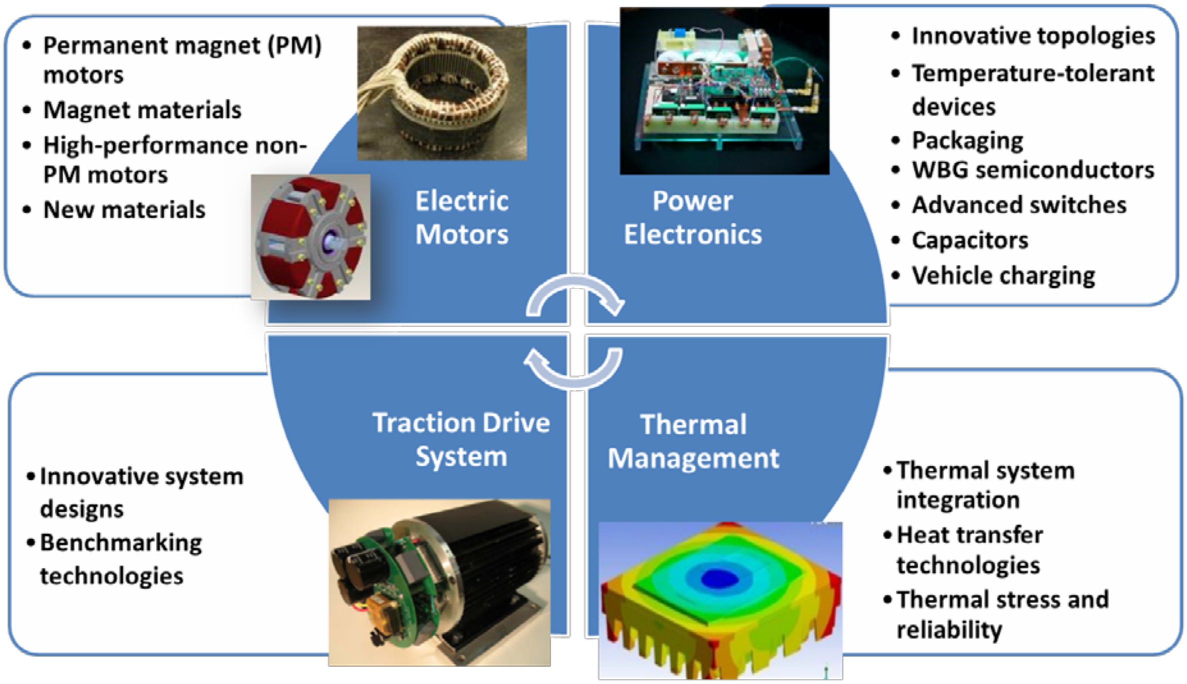


Figure 7. PEEM Research Focus Areas

Focus Area: Motors

Candidate motor types suited to light duty propulsion applications include:

- induction
- interior permanent magnet
- surface permanent magnet
- variable reluctance
- switched reluctance.

These candidates are also shown across the bottom of Figure 8.

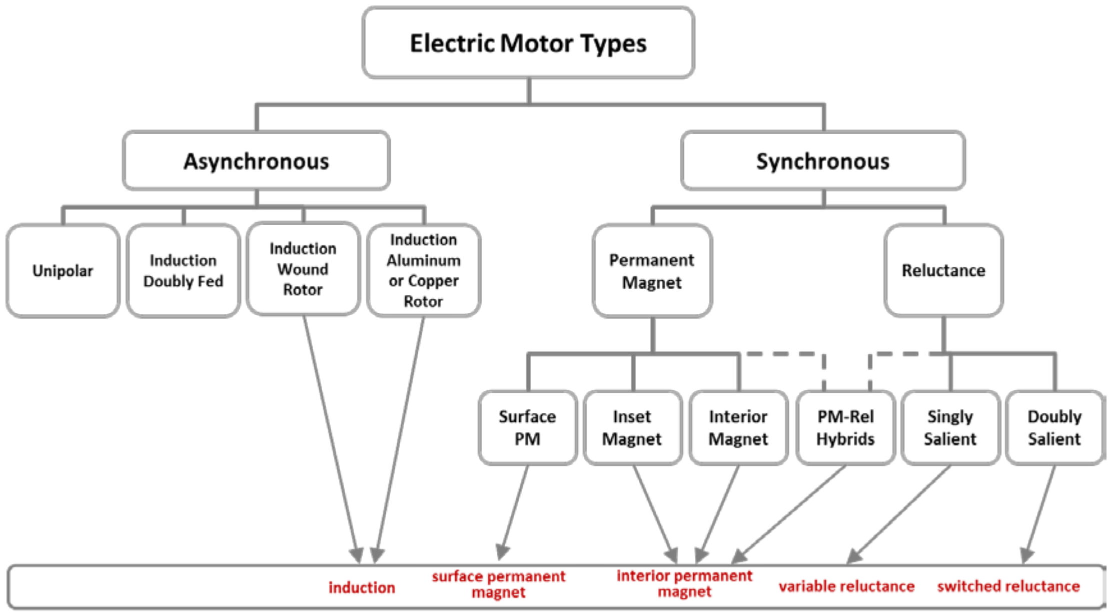


Figure 8. Types of Motors

Table 8 shows the research areas that are being pursued with respect to motors.

Table 8. Research Areas for Motors

Research Area	Impact
PM Motors *Reduce cost & maintain performance*	Cost is a major concern for IPM motors (cost reductions of 75% are required to meet 2020 target). Work on all aspects of motor design may reduce cost by 25% to 40%.
Magnet Materials *Reduce cost & increase temperature*	Magnetic materials cost 50% to 75% of the motor targets for 2015 and 2020, respectively. Work should focus on reducing cost and increasing temperature capability which could reduce motor cost by 5% to 15%.
Non-PM Motors *Reduce cost & maintain performance*	Non-PM machine technology matching the performance of IPM motors yields the greatest opportunity for motor and system cost reduction • PM cost of $200 is about 75% of the 2020 motor cost target; eliminating PMs reduces motor cost by 30% • Increase constant power-speed ratio (CPSR) to 8:1 (current systems are 4:1) to effect savings in transmission
Other Materials *Reduce motor cost*	Other materials in the motor must be addressed because PMs are about 30% of current IPM cost. New materials for laminations, cores, etc., could save 20% of motor cost.

Research Area: PM Motors

Because of their superior power density and specific power, IPM motors have become the industry workhorse in HEV applications, and this is anticipated to hold true for the next decade. The 2015 and 2020 cost targets for the traction motor are $385 and $260, respectively. To achieve the 2015 and 2020 cost targets, the motor cost must be reduced by 40 % (for 2015) and 60% (for 2020). This requires reductions in all cost elements in the motor and the application of advanced materials, designs, and manufacturing processes. Investigation of motor designs that use less-costly PMs is also needed.

Research Area: Magnet Materials

Current IPM motors use neodymium iron boron PMs because of their superior magnetic properties. However, these magnets are expensive; in a typical 55 kW IPM, the magnets cost in the range of $100 to $200 (this is about 50% of the 2015 motor cost target and 60% of the 2020 motor cost target). In addition, demagnetization at elevated temperatures poses limits on the motor that require either limiting the duty of the motor or investing in thermal management systems to transport heat from the motor. Magnet materials that possess magnetic properties similar to neodymium iron boron magnets but cost less and have higher temperature limits are needed if the IPM has a reasonable chance of meeting the cost targets.

Research Area: Non-PM Motors

Because of the disadvantages of IPM motors noted above, the development of motors that do not use permanent magnets but yield IPM-like performance is being pursued. This program includes R&D to solve issues with existing motor designs that will allow their use in advanced vehicle applications, such as switched reluctance motors, as well as developing new novel designs.

Research Area: New Materials

Achieving cost targets will require improvement in all design elements of the motor. Because of their prominence in the motor cost, permanent magnets have been given much attention. However, they represent only about 30% of the motor cost for existing IPM designs. Attaining the levels of cost reduction required to meet 2015 and 2020 motor cost targets requires expanding the effort to all materials in the motor. New lamination materials, soft magnetic core materials, and a number of other alternatives should be examined, since they may enable new design freedoms that can reduce the gaps in reaching the targets.

Focus Area: Power Electronics

The major power electronic modules are inverters (which may or may not include a boost DC/DC converter), power-conditioning DC/DC converters, and chargers.

Inverters

A major focus of the power electronics R&D is on inverters, which are required to drive all of the electric motors as part of ETDS in HEVs, PHEVs, and BEV/FCVs. The specific design may vary, as will the power rating, number of phases, topology, and module packaging method. The decision on the inverter design is intimately tied to the type of motor that the inverter must drive; the inverter and motor must operate as a system efficiently and seamlessly.

DC/DC Converters

HEVs, PHEVs, BEVs, and FCVs will require low-voltage buses for traditional vehicle loads and, therefore, require a step-down DC/DC converter from the high-voltage buses. Most applications will require a power-conditioning DC/DC converter with a relatively high power rating of 3 to 5 kW continuous for auxiliary loads. The converter also needs to provide galvanic isolation between the low- and high-voltage buses. Furthermore, soft switching is preferred over hard switching because of the reduced level of EMI and switching losses. Other expected requirements for this converter are:

- The terminal voltage of the battery can swing from 8 V to 16 V during either direction of power flow.
- The nominal voltage of the high-voltage bus is 325 V, with an operating range of from 200 V to 400 V.

Bi-Directional DC/DC Converters

Issues related to bi-directional DC/DC converters and boost DC/DC converters are similar to those for inverters except they also include inductors, which are heavy and bulky.

Chargers

The charger design involves not only understanding the vehicle environment and its electronic circuitry but also the AC supply infrastructure. In designing PHEV chargers that interface with the utility grid system, design considerations must be given to the impacts on the electrical grid, residential EMI emissions and susceptibility, UL standards, SAE standards, The National Electric Code, and owner safety.

Battery chargers for PHEVs can be based upon proven, traditional, high-frequency charger circuits and can be located either on or off board the vehicle. Ground fault circuit-interrupter outlets and breakers can be sensitive to high-frequency power supplies. Additionally, on-board concepts that integrate the charging function into the existing power electronics and utilize the inductance of the motor can be developed. Safety and ensuring high voltage isolation is of paramount importance to any design. Conductive and inductive charging designs each have benefits. In all cases, designs must be realized with a small footprint, be light-weight, and have low cost, high efficiency, and high reliability.

The power electronics focus area for inverters and converters have common areas of research. Table 9 shows the research areas that are being pursued with respect to the power electronics. A common theme amongst the research areas is the desire to improve the components temperature tolerance which will greatly improve the reliability and lifetime operation while decreasing the thermal management requirements.

Table 9. Research Areas for Power Electronics

Research Area	Impact
Innovative Topologies for Power Modules *Decrease size and 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 the power electronics size and cost and increasing reliability • Reduce inductance, minimize EMI and ripple, and reduce the current through switches resulting in lower cost
WBG Semiconductors Advanced Switches *Enable high temperature operation*	Enables higher efficiency, higher temperature operation, and a more compact inverter package
Packaging *Greatly reduce 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%, and enable Si devices to be used with high-temperature coolant for cost savings of 25%, • Device packaging to reduce stray inductance, improve reliability, and enable module packaging options When coupled with heat transfer improvements, gains are enhanced
Capacitors *Reduce inverter volume*	Improved performance can reduce capacitor size by 25%, reducing inverter size by 10%, and increasing temperature limit

Research Area: Innovative Topologies for Power Modules
The major components of power modules that need to be addressed include:

Semiconductor Switches. Current state-of-the-art inverters use insulated gate bipolar transistors (IGBTs) for high-power and high-voltage applications, such as automotive traction drives and metal oxide semiconductor field effect transistors (MOSFETs) for low-voltage, low-power applications. Standard IGBTs are only capable of switching up to 20 kHz compared to several hundred kilohertz for MOSFETs. The high on-resistance of standard MOSFETs prevents their application at 600 V and above for high-power conversion. High switching frequencies associated with WBG devices are desirable to reduce the size of capacitors and magnetic components, but the cost, availability, and their reliability have prevented their application.

Semiconductor switches have a large impact on the cost of the inverter, typically accounting for about 33% of the total cost. They also have an indirect effect on size and weight of the system because of the cooling requirement to keep the junction temperature of the device below 175ºC for IGBTs and MOSFETs.

New IGBTs based on trench technology show significant improvements over the non-punch-through IGBT. Both the saturation voltage and the switching losses are reduced by about 20% along with an increase in the allowable junction temperature to 175°C. To take advantage of this higher temperature rating, new packaging technologies must be explored. SiC is a long-term attractive alternative to Si because SiC devices can operate at temperatures up to 350ºC, and they have high thermal conductivity, higher breakdown voltages, low switching losses, and the capability to operate at high switching frequencies. The main problem is cost; SiC is more expensive than Si, production quantities are low, and scrap rates are high because of immature manufacturing processes.

A considerable amount of research focusing on WBG devices is being conducted by the military and the electronics industry. In view of the comparatively small effort that could be funded by the automotive industry and the very small market share represented by the automotive industry, the strategy with respect to semiconductor switches consists of monitoring the research conducted by other organizations and testing devices for automotive applications as they become available. Recently, though, the potential of SiC in some automotive applications may dictate the specific development by the industry of devices, such as SiC diodes, to increase inverter efficiency.

Heat Exchanger: Another major contributor to the weight and volume of an inverter is the heat exchanger; discussed further in the section on thermal management.

Research Area: Advanced Switches (WBG)

Advanced WBG (SiC and GaN) switches require rethinking of automotive power electronics design and application. These new devices can provide higher efficiency and tolerate higher operating temperatures than today's Si devices. The capability of these devices to withstand transient events needs to be explored further. These attributes of WBG devices need to be translated into application benefits for the automotive consumer. New packaging, topologies, new gate drive controls and passive components need to be developed in order to gain these vehicle benefits.

Research Area: Packaging

Attaining the size, weight, and cost reductions and reliability requirement needed to meet the 2015 and 2020 targets will require innovative module and device packaging. At the module level, the elements associated with removing heat (the spreader, thermal interface material, and heat exchanger) occupy a substantial volume. Industry trends associated with cost reduction paths are likely to result in these elements getting larger. The desire to reduce cost by using less Si will increase the heat flux that must be accommodated, which will increase the size of these heat rejection components. Integrating the power electronics cooling system with an existing cooling system (as a means of reducing cost) is likely to result in higher-temperature coolants that will further exacerbate the situation. If packaging advances are not made, the volume implications of these trends are that the volume of the heat transfer components themselves could equal or exceed the inverter volume targets for 2015 and 2020. Innovative module packaging can mitigate these size increases by eliminating existing interface layers and providing cooling at or very near the heat sources, as well as by increasing the heat transfer rates. This could also enable high-temperature coolants to be used with existing Si devices, resulting in further potential cost savings.

Packaging innovations could also result in reliability and performance improvements through optimized bus structures, die-attach methods, and materials that provide thermal-expansion matching. Advanced device packaging could also result in packing techniques (such as three-dimensional formations) that would contribute greatly to achieving volume targets.

Power electronics packaging improvements go beyond just looking at semiconductor-device-level innovations. There are opportunities to reduce size, weight, and costs of the power electronics through improvements in gate-drive packaging, current sensors, and capacitors and magnetics that will provide better performance and more reliable and higher temperature operation.

Research Area: Capacitors

Capacitors typically represent one of the larger cost components of an inverter, and they also account for a major portion of the volume and weight. Materials that offer improve dielectric properties, higher temperature capabilities and low equivalent series resistance (ESR) are needed to reduce the overall volume. Polymer-film capacitors are used in most HEVs today, but they currently cannot tolerate sufficiently high temperatures for future applications that will require 150°C. Many current polymer-film capacitors typically are rated at 85°C, but more-expensive ones are available that can operate up to

105°C. Ceramic capacitors have excellent performance characteristics, but cost, reliability, and achieving a benign failure mode remain issues.

Focus Area: Thermal Management

The thermal management system is a critical enabling technology for increased power density, but it has been historically treated as an add-on to the system after other components and packaging are designed. The overall technical challenge for thermal management of automotive PEEM systems is to develop an efficient and reliable method for removing several kilowatts of heat in a confined space under harsh ambient conditions without adding to the overall system cost, complexity, or parasitic-power requirements. The need to decrease volume and the desire to eliminate the separate cooling system added significantly to the thermal management challenges. Therefore, a critical part of the PEEM portfolio includes the following thermal management research shown in Table 10. The overall intent of the Thermal Management focus area is to enable increased power density and lower cost for PEEM components, improve the reliability of new technologies, as well as develop predictive lifetime models that can help reduce design costs.

Table 10. Research Areas for Thermal Management

Research Area	Impact
Thermal System Integration *Enable technology integration at lower system cost*	• Define thermal requirements • Demonstrate viable thermal solutions for PEEM components • Link thermal technologies to ETDSs systems • Provide pathways to combining cooling loops in electric-drive vehicles
Heat Transfer Technologies *Enable increased power density at lower cost*	• Provide pathways to reduce thermal resistance in the passive stack-up in PEEM components • Provide detailed modeling and experimental characterization of the thermal performance of feasible cooling technologies
Thermal Stress and Reliability *Improve reliability of new technologies*	• Develop advanced predictive thermal stress and reliability modeling tools • Provide an experimental reliability assessment of emerging technologies • Guide research decisions, streamline development and design time, and identify potential barriers to meeting life and reliability goals

Research Area: Thermal System Integration

The objective of this research area is to facilitate the integration of PEEM thermal management technologies into viable advanced ETDSs. There is a wide variety of potential thermal technologies; a given thermal solution can impact the component design space including package/module configuration, architecture, and material selection. Conversely, these parameters, along with the vehicle architecture, define the thermal requirements. Rapid parametric models are being developed and applied early in the design process to help select the most appropriate thermal management technology for a given traction drive system. Inputs into the models include fundamental heat transfer performance characteristics, component geometry, various material properties, and a range of system thermal requirements. Outputs include both steady-state and transient thermal loading and component temperatures under various conditions.

This research area is focused on understanding the tradeoffs and matching the thermal requirements of the electric traction drive with a range of packaging options, development of inverter- and motor-scale heat exchangers, and investigation of combined cooling loops in electric-drive vehicles for reduction of cost, weight and volume.

Research Area: Heat Transfer Technologies
This research area seeks to provide an accurate and objective characterization of the thermal performance of heat transfer technologies within the context of automotive requirements, and to further develop and demonstrate the promising technologies that enable reductions in cost, volume, and weight. On the characterization side, this research includes fundamental characterization of heat transfer technologies such as the performance of single-phase liquid (water-ethylene glycol, transmission oil) and two-phase jets and sprays, air-cooled heat exchangers, pool-boiling techniques (with dielectrics and refrigerants), surface-area-enhancement techniques as well as materials/interfaces thermal performance. Detailed numerical modeling of the technologies such as computational fluid dynamics and finite element analysis are used to further understand the heat-transfer mechanisms and the conditions under which these technologies may be suitable for electric traction-drive cooling.

Research Area: Thermal Stress and Reliability
This research activity will develop predictive modeling capabilities to assess the impacts of thermal stress on the life of advanced inverter package designs and other PEEM components. The impact of thermally induced stress on the life of advanced packages/modules is linked to the impact of thermal stress on individual layers within the package/module (e.g., bonded interfaces and electrical interconnects). Thermally induced stress is a major issue related to reliability, which is directly linked to heat dissipation and the package/module configuration. Vehicle manufacturers and component suppliers must run extensive life and reliability testing on all new technologies and designs to understand the response to thermal cycling and environmental conditions.

This effort will closely engage industry to develop and validate advanced predictive modeling processes using techniques such as "physics of failure" to evaluate the impacts of new technologies on thermal stresses, life, and reliability. The ultimate goal is to reduce the amount of testing and the cost and time to market for new technologies. Predictive modeling tools, applied early in the development process can help guide research decisions, streamline development time, and identify potential barriers to meeting life and reliability goals. Finite element modeling techniques will be used in conjunction with accelerated testing (e.g., thermal cycling, thermal shock) to identify failure modes and relative impacts on reliability beyond what is currently available in the open literature. The scope of the research also includes improvements in the processing/synthesis techniques in order to improve the reliability of the components.

Focus Area: Systems
Ultimately, an ETDS must be developed that meets the overall vehicle system requirements. The design choice of the motor technology will dictate the type of power electronics and controller necessary to drive the particular electric motor. It is essential to develop an advanced ETDS that can plausibly be manufactured and is compatible with automotive high-volume production. It also is critical to develop a vehicle-level electrical and electronic infrastructure that accommodates the motor and its electronics for ensuring system reliability and safety. The development of this infrastructure must not be overlooked.

Although new technologies may not appear to merit incorporation on a standalone basis, but, when incorporated with other technologies in a system, they may provide significant improvement. Making the significant improvements that are needed in the performance and cost of the traction system will require the integration of motors, power electronics, and thermal management technologies. When combining these technologies, considerations must be made for vehicle applications, flexibility, and overall system benefits.

Research Area: Innovative System Design

To significantly reduce system weight, cost, and volume, concepts must be developed that are capable of reliable higher-temperature operation. To attain the long-term goals, concepts that advance the state of the art in the following areas must be considered:

- Modularity
- Integration
- Advanced cooling technologies
- Inverter and motor topologies
- Packaging innovations
- Buss structures
- Semiconductor devices
- Capacitors
- Sensors
- Magnetics
- Cabling
- Disconnects
- Galvanic isolation
- Power electronics manufacturing processes
- Motor manufacturing processes.

Research Area: Benchmarking

Benchmark testing of HEV drive trains and power electronics and electric motor components is an integral part of the program and complements the R&D portfolio. It is performed to fully characterize the performance of the technology and evaluate and analyze innovations across the complete range of electrical and thermal parameters that are applicable for vehicle applications, and it is coordinated with the vehicle-level benchmarking within the DOE Vehicle Technologies Office. In most cases, this information is not available from the manufacturer.

Appendix A: Acronym List

AC	alternating current
BEV	battery electric vehicle
CPSR	constant power-speed ratio
DC	direct current
DOE	U.S. Department of Energy
EESTT	Electrochemical Energy Storage Tech Team
EETT	Electrical and Electronics Technical Team
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EREV	extended-range electric vehicle
ETDS	electric traction drive system
FCV	fuel cell vehicle
GaN	gallium nitride
GITT	Grid Interaction Tech Team
HEV	hybrid electric vehicle
ICE	internal combustion engine
IGBT	insulated gate bipolar transistor
IM	induction motor
IPM	interior permanent magnet
ISG	integrated starter-generator
kg	kilogram
kW	kilowatt
MOSFET	metal oxide semiconductor field effect transistor
MPG	miles per gallon
MPGe	miles per gallon equivalent
MSRP	manufacturer’s suggested retail price
NVH	noise, vibration, harshness
OEM	original equipment manufacturer
PEEM	Power Electronics and Electric Motors
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
PIM	power inverter module
PM	permanent magnet
R&D	research and development
SiC	silicon carbide
USCAR	United States Council for Automotive Research LLC
U.S. DRIVE	United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability
VDC	volts direct current
V	volts
VSATT	Vehicle Systems Analysis Tech Team
WBG	wide bandgap