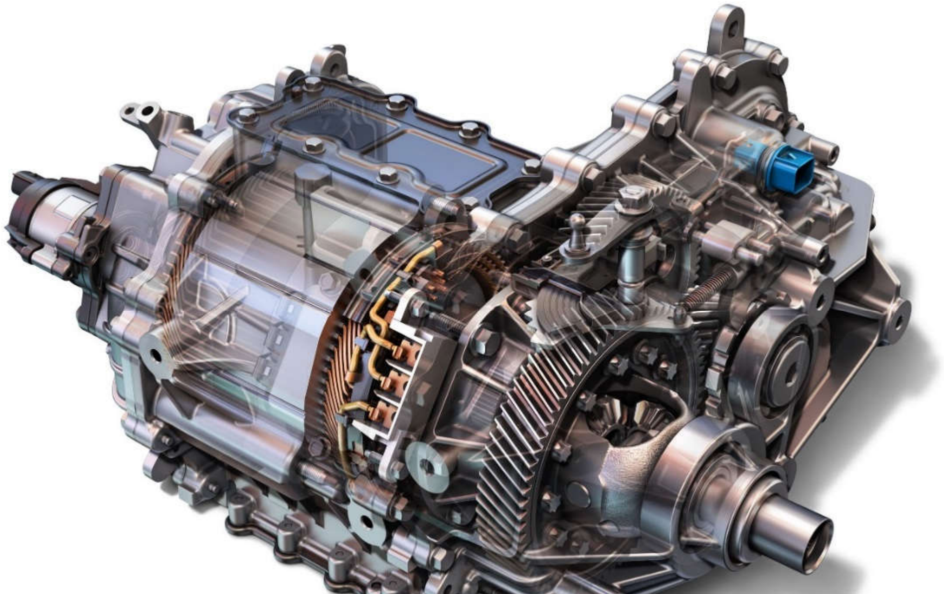
DRIVING RESEARCH AND INNOVATION FOR
VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Electrical and Electronics Technical Team Roadmap

October 2017



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 non-legal partnership among the U.S. Department of Energy; USCAR, representing FCA US LLC, Ford Motor Company, and General 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).

Electrical and Electronics Tech Team is one of 13 U.S. DRIVE technical teams that work 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.

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

Executive Summary

Electric traction drive systems (ETDS) have experienced significant changes over the past 20 years. Battery electric vehicles with a range of 200 to 300 miles are available today with equivalent or better performance than comparable internal combustion engine (ICE) vehicles. Electric vehicle charging (refueling) at home has become a feature highly valued by consumers, and fast-charging capability brings the promise of refueling times comparable to ICE vehicles. In the last 2 years this drastic improvement in vehicle electrification has coincided with a radical transformation of society's understanding of mobility. Historically, personal vehicles have opened the door to freedom-of-movement and self-expression, but now transportation is available as a service (oftentimes called mobility-as-a-service, or MaaS). These changes—improved electrification and transformed mobility—drive the four fundamental trends impacting the Electrical and Electronics Technical Team (EETT):

1. Adoption of electrified skateboard chassis that includes both the electric traction drive system and energy storage. This provides greater vehicle design freedom, more usable passenger space, and a modular platform to increase production scale.
2. MaaS trades the traditional ownership model driven by personal taste for a fleet ownership model driven by lifecycle cost. This drives on-board power and electromagnetic interference requirements, autonomous and extreme fast charging, and the need to maximize usable space on the vehicle.
3. Production scale needed for mass market viability has moved from 100,000 to 500,000 units per platform. This has been driven by intense competition in the auto industry.
4. Vehicle performance requirements are driving demand for higher-power ETDS. Consumers want significantly faster acceleration and larger, more versatile vehicles.

These trends require that ETDS design evolves rapidly to achieve and maintain commercial success. The systems must fit in a skateboard chassis requiring nearly an order of magnitude (8x) increase in power density, have twice the reliability (300,000 miles), and be modular and scalable for use on vehicle platform variants, all while producing higher power. Achieving this will require heterogeneous or multi-physics integration of materials, nano-carbon infused metals, a new class of isolation materials, high-temperature materials, and new thermal management techniques. Additionally, there is a need to understand and quantify the physics of materials and their interactions under extreme power and temperature. This document describes the research and development necessary to achieve the future vision of energy-efficient transportation which is vital for both increased personal mobility and continued U.S. economic growth.

This roadmap was developed collaboratively through an iterative process to ensure it represents a united vision of industry and government stakeholders. The EETT OEM partners were actively involved in the 2025 target development process. Technology gaps and strategy to achieve the targets are based on OEM and supplier input. Industry engagement took the form of a face-to-face multi-day meeting and individual company follow up throughout the course of roadmap development. As a result, the roadmap includes two specific technical guidance documents, one for power electronics and one for electric motors (included in the appendix), which were driven by the OEMs and confirmed by the suppliers. The gap between current technology and the 2025 technical targets defines the need for new technologies, material advancements and new manufacturing processes. OEM, supplier, and national laboratory engagement were instrumental in developing the strategy for this roadmap.

The chosen strategy to overcome current barriers and achieve the technical targets is to conduct R&D with industry input aimed at achieving a significant technology push. DOE national laboratories are working with the supply base to improve wide bandgap-based power electronics and non-rare earth or magnet-less electric motors to meet the 2025 ETDS R&D targets. Component targets and material requirements were identified and reviewed with suppliers. Supplier-based solutions were encouraged as the national laboratories focus on early-stage research to close the technical gaps in knowledge and on conducting system and component tradeoffs (see Figure ES-1). This will result in basic technology building blocks to be used as inputs for automotive OEM advanced development groups. The OEMs will provide guidance by reviewing requirement development and conducting design reviews. Program status is evaluated in relation to the technical targets on an annual basis.

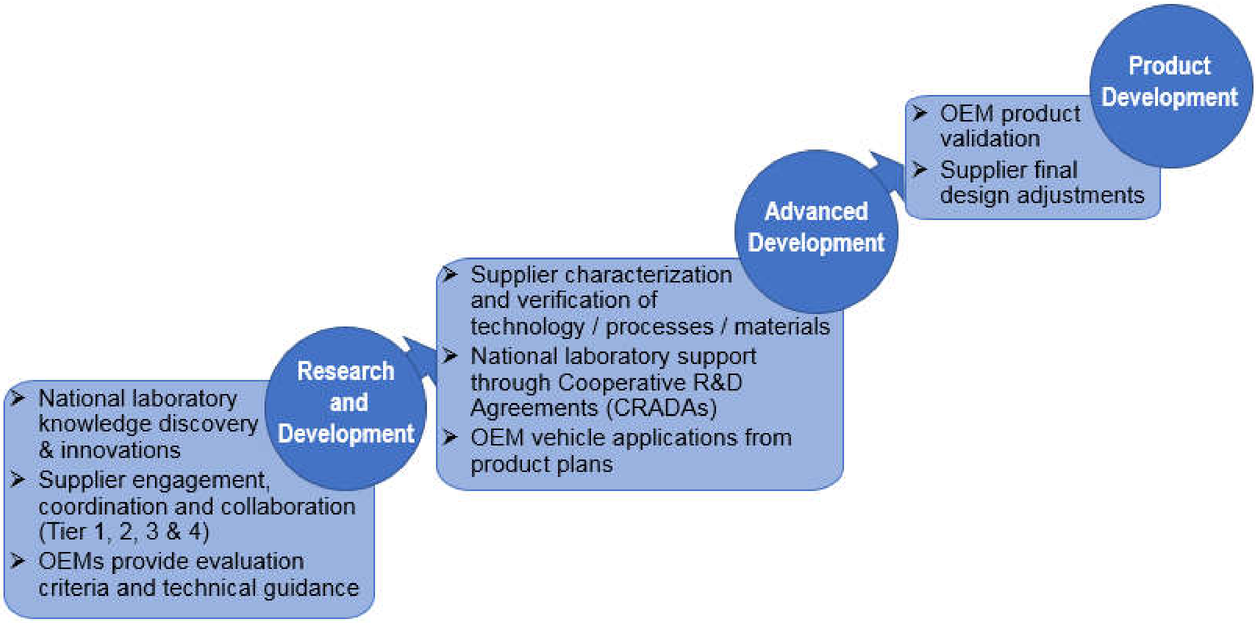


Figure ES-1. Automotive Product Development Cycle

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Acronyms

AC	alternating current
AIPM	advanced integrated power module
AEMD	advanced electric motor design
BEV	battery electric vehicle
CAV	connected and autonomous vehicle
CUV	crossover utility vehicle
DC	direct current
DCFC	direct current fast charger
DOE	U.S. Department of Energy
EDV	electric drive vehicle
EETT	Electrical and Electronics Technical Team
EMC	electro-magnetic compatibility
EMI	electro-magnetic interference
EREV	extended-range electric vehicle
EESTT	Electrochemical Energy Storage Tech Team
ETDS	electric traction drive system
EVSE	electric vehicle supply equipment
FCEV	fuel cell electric vehicle
GITT	Grid Interaction Tech Team
HEV	hybrid electric vehicle
ICE	internal combustion engine
LDV	light duty vehicle
MaaS	mobility-as-a-service
NdFeB	neodymium iron boron
NVH	noise, vibration and harshness
OBC	on-board charger
OEM	original equipment manufacturer
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
PIM	power inverter module
PM	permanent magnet
R&D	research and development
SUV	sport utility vehicle
USCAR	United States Council for Automotive Research LLC
U.S. DRIVE	United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability
VSATT	Vehicle Systems Analysis Tech Team
WBG	wide bandgap
WPT	wireless power transfer
XFC	extreme fast charging

Team Mission and Scope

Mission

To support the mass market adoption of electric drive vehicles, the mission of the Electrical and Electronics Technical Team (EETT) is to accelerate the development of cost-effective and compact electric traction drive systems (ETDSs) that meet or exceed performance and reliability requirements of internal combustion engine (ICE)-based vehicles, thereby enabling electrification across all light-duty vehicle types.

The EETT mission supports U.S. DRIVE's Vision that "American consumers have a broad range of affordable personal transportation choices that reduce petroleum consumption and significantly reduce harmful emissions from the transportation sector." It also directly supports U.S. DRIVE's Mission to "accelerate 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." This mission is specifically embodied in the following goal:

> *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.*

As part of this U.S. DRIVE Partnership goal, EETT has a specific 2025 Partnership Research Target*:*

> *An electric traction drive system at a cost of $6/kW for a 100 kW peak system.*

In addition to the U.S. Drive Partnership level target, EETT has a 2025 power density research target of 33 kW/L for a 100 kW peak system. While achieving this target will require transformational technology changes to current materials and processes, it is essential for enabling widespread electrification across all light-duty vehicle platforms.

Scope

The EETT focuses on pre-competitive, early-stage research and development of ETDSs (consisting of electric motor[s] and inverter[s]), that drive the following electric drive vehicle (EDV) configurations:

- hybrid electric vehicles (HEVs)
- plug-in hybrid electric vehicles (PHEVs)
- extended range electric vehicles (EREVs)
- battery/fuel cell electric vehicles (BEVs and FCEVs)

Depending on the vehicle type and system architecture, other power electronics besides the inverter might also be included and are covered by the EETT, such as:

- power transfer components (on-board charger and wireless charging components)
- bi-directional DC/DC converter
- voltage step-down (buck) DC/DC converter

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

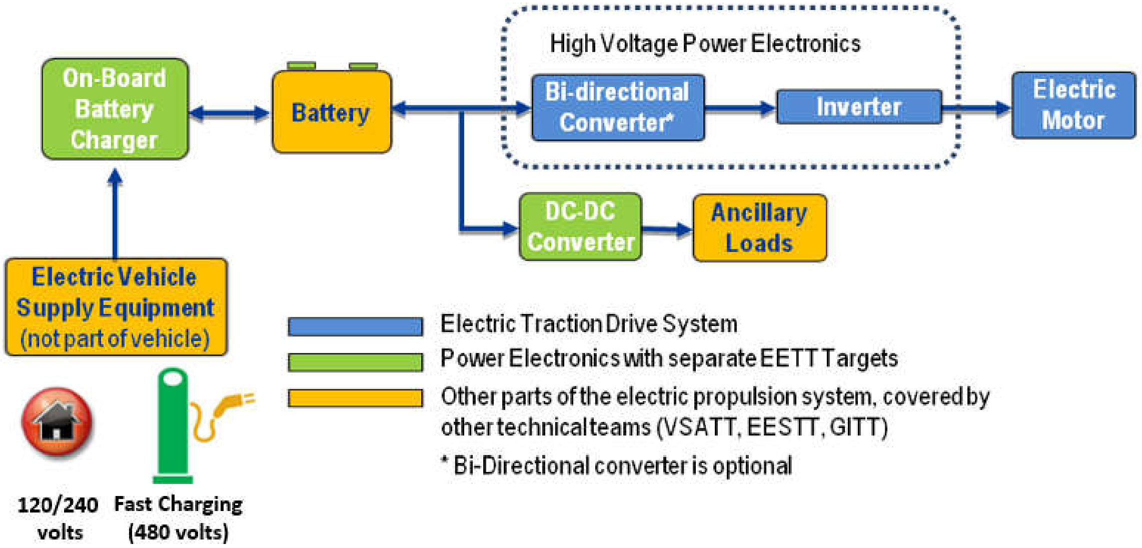

Figure 1. Components of Generic ETDS

The ETDS is delineated by the bi-directional converter's DC Bus to the battery and the electric motor output shaft (all components highlighted in blue in Figure 1). The main power transfer component is the on-board battery charger (OBC) which is also covered by EETT targets. In case of wireless power transfer (WPT) or extreme fast charging (XFC) vehicle capability the EETT is responsible for all related power electronics components on the vehicle as well as interfaces to the off-board components necessary for their operation. For research related to WPT and XFC, EETT coordinates efforts with the Grid Interaction Tech Team (GITT) and Vehicle Systems Analysis Tech Team (VSATT).

The OBC is bounded by the external AC electrical interface to the Electric Vehicle Supply Equipment (EVSE) and the DC Bus to the battery. The OBC interfaces are governed by the GITT, VSATT and Electrochemical Energy Storage Tech Team (EESTT). The EETT coordinates OBC efforts and research goals with those teams to develop reasonable and balanced research goals and ensure that one system is not optimized at the expense of an interfacing system (e.g., EVSE, high voltage battery, or gearbox/transmission). Research goals also consider the vehicle constraints related to electromagnetic compatibility (EMC) and noise, vibration and harshness (NVH).

The EETT Roadmap focuses on pre-competitive research and development (R&D) to enable increased vehicle electrification. Ideally, each new and innovative technology will be modular and scalable to broaden its applications. Most common relevant vehicle architectures are illustrated in Table 1 below; other uses and applications exist such as electric all-wheel drive for PHEVs (single motor) and performance EVs with 2 to 4 traction motors. Historically EETT R&D focused on HEVs, but the focus has shifted to full electric drive vehicles, which include: PHEVs, EREVs, BEVs and FCEVs. Full EDV system layouts are shown in Figure 2.

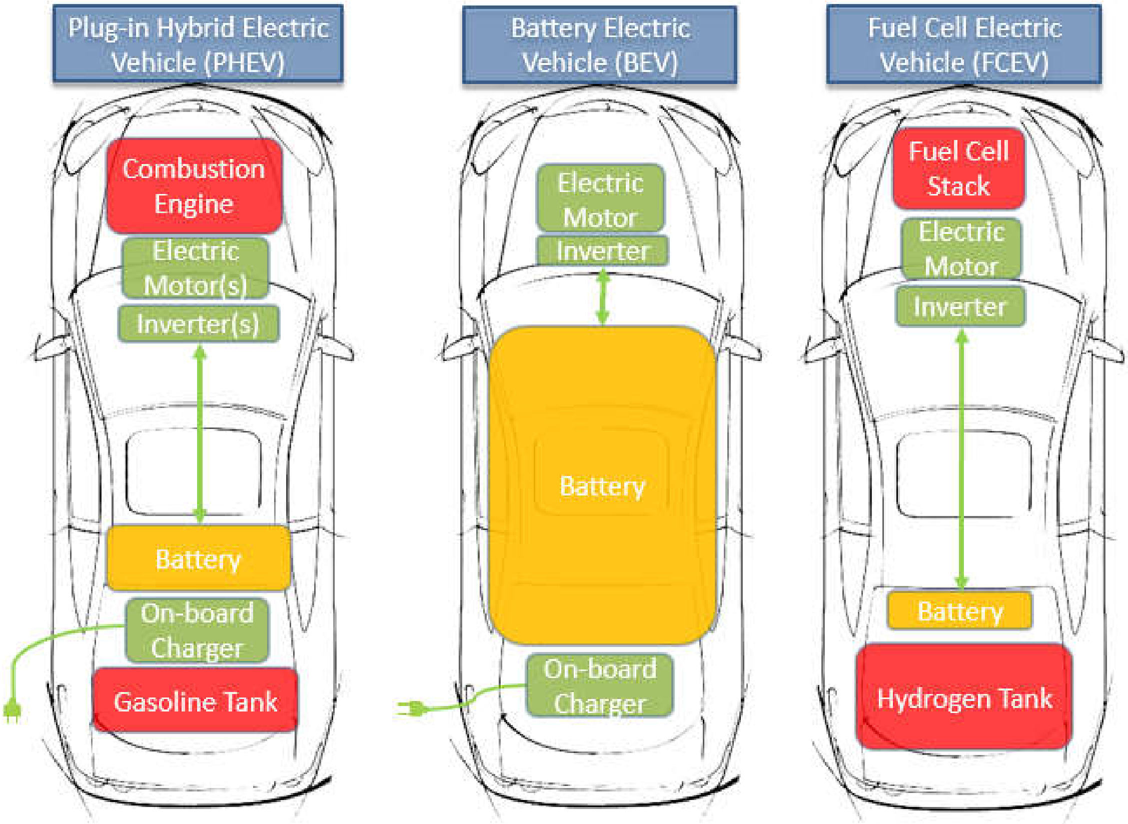

Figure 2. EDV Architecture Layouts

Table 1. Key EDV Architecture Characteristics

ETDS Key Parameters	PHEV and EREV	EV (BEV or FCEV)
ETDS Usage	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 Power Inverter Modules (PIMs) Required	2 - traction and generator	1 - traction only
Peak Mechanical Output Power (kW)	50-125	80-270

Key Challenges to Technology Commercialization and/or Market Penetration

Market Status

EDV share of annual new vehicle sales (including HEVs) has been hovering around 3 percent since 2012, as shown by the dashed green line in Figure 3. There was a relatively limited number of EDV models early on, but that number exceeded 30 at the beginning of 2017 for plug-in electric vehicles (PEVs); half of which are BEV models. Part of the reason for the low sales penetration is that EDV models are generally smaller passenger vehicles, while more than 50 percent of the light-duty vehicle (LDV) sales in the U.S. market are light-duty trucks, which include sport and crossover utility vehicles (SUVs and CUVs respectively). Another detrimental factor is the lack of PEV availability nationwide; many models are only offered in specific states.

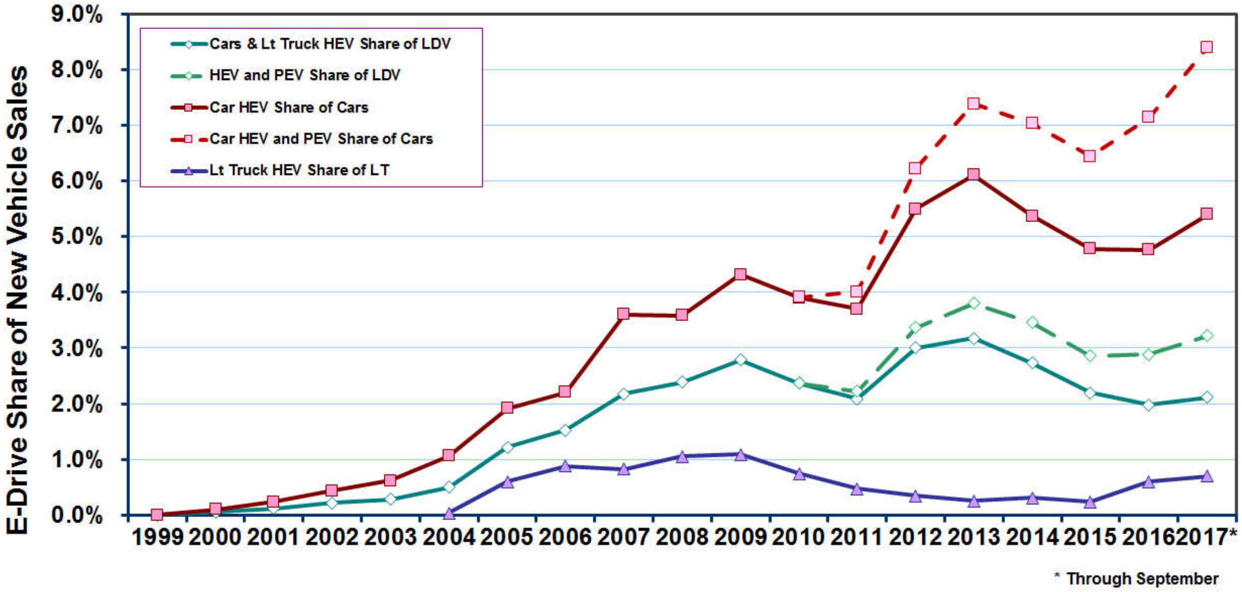

Figure 3. Light Duty Electric Drive Vehicles Monthly Sales Updates
Source: Argonne National Laboratory, Energy Systems

Historically, the EETT focus was on HEV applications and the targets were based on a 55 kW peak power level. As the number of EDV models offered by the original equipment manufacturers (OEMs) is increasing and starting to include larger and heavier vehicles (i.e., SUVs and CUVs), the ETDS power level requirement is also increasing as shown in Figure 4 (the error bars show the range of peak power levels). Consumer vehicle performance expectations are also a contributing factor to the higher power levels. In response, the 2025 EETT peak **power level target** was increased to **100 kW**. As the vehicle size increases, PHEV models seem to dominate due to lower incremental costs without compromising the driving range in comparison to BEVs. Electrifying SUVs and CUVs into PHEVs also provides an opportunity to add all-wheel drive capability without occupying space between the front and rear axle.

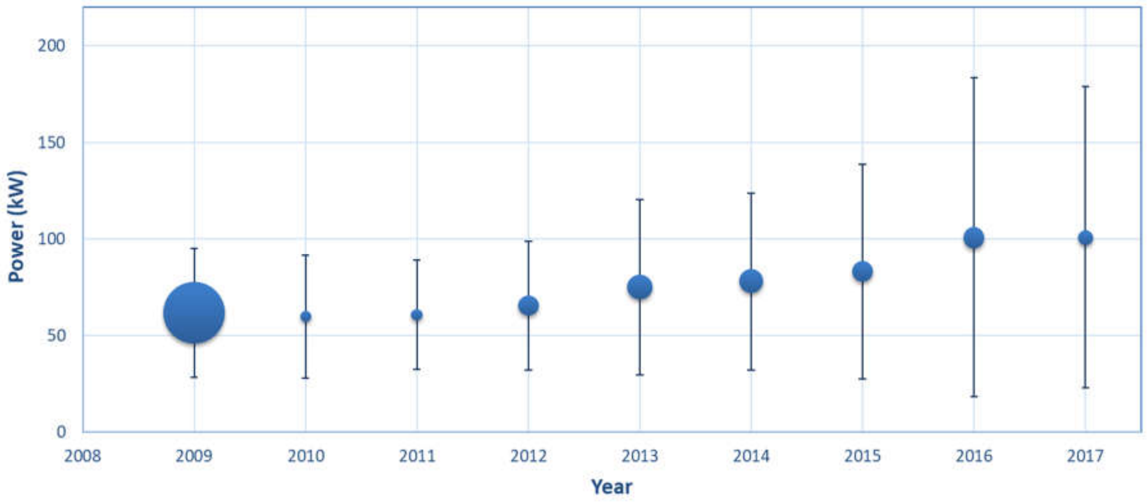

Figure 4. Average Combined ETDS Peak Power for HEVs and PEVs 2010-2016 (bubble size represents relative annual sales and "2009" includes data from prior years. 2017 data through September.

Source: Argonne National Laboratory, Energy Systems

Key Challenges: Cost and Size

The two main challenges to wider availability of EDV models are incremental cost and size of both ETDS and energy storage. The cost of energy storage has been significantly reduced since the first EDV model introductions in 2010, but is still a limiting factor for BEVs due to a large energy capacity required for adequate driving range. PHEVs and EREVs also incur unique packaging constraints due to the need for both the electrified powertrain (ETDS and energy storage) and the conventional ICE powertrain. Therefore, to achieve significant EDV market penetration, for example 10 percent by 2025 and 35 percent by 2040 as suggested in Figure 5, ETDS cost and size will need to be reduced even further in addition to continued reduction in energy storage costs. This will in turn allow for easier integration of ETDS and favorable economics, resulting in a greater number of both passenger and light truck EDVs.

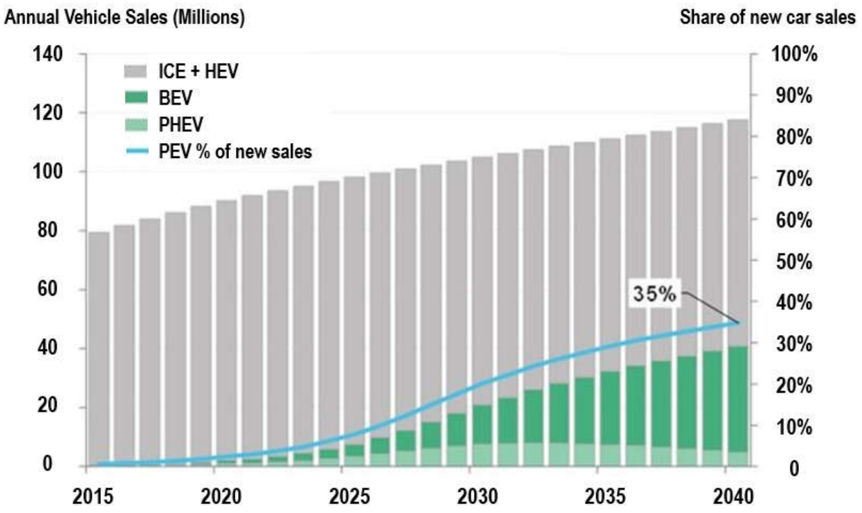

Figure 5. Projected EDV Sales

Source: 2016 Blomberg New Energy Finance

Future Trends

BEVs seem to be the platform of choice for connected and automated vehicle (CAV) developers due to the design freedom that a modular skateboard chassis architecture allows (see example in Figure 6). Many manufacturers aim to launch CAVs in mobility-as-a-service (MaaS) applications (e.g., car-share, ride-share, ride-hailing) between 2020 and 2025 due to their lower operating costs. This transforms the vehicle value proposition from performance, fuel savings, and personal satisfaction to reduced operating cost, increased uptime, and per-mile monetization potential. Such high-use, taxi-like applications require very high operating times, where vehicles can accumulate between 50,000 and 80,000 miles annually. Some consumers may switch transportation modes due to perceived comfort or lower cost; for example, some short air or train miles traveled could be replaced with MaaS on-road autonomous vehicle miles. To ensure adequate durability for CAVs in MaaS operation, the 2025 ETDS life expectancy target was increased from 150,000 to **300,000 miles** for 2025.

Automakers that are developing long-range BEVs are taking a modular chassis approach where the ETDS and energy storage are integrated into the skateboard-like flat chassis. Depending on the amount of energy storage needed, the chassis can be stretched to accommodate vehicles of various sizes. While traditional ETDS manufacturing volumes were based on conventional automotive manufacturing standards of 100,000 annual production units, this change in design, enabling multi-platform use, increases the EETT 2025 annual manufacturing volume assumption to **500,000 units**.

Figure 6. 2017 Chevrolet Bolt BEV Chassis with Powertrain (left); Example of a Flat Skateboard Chassis Containing Electric Powertrain (right).
Source: General Motors

Charging needs for future 300+ mile BEVs with larger energy storage will also need to be addressed differently. In early 2017, 20 to 50 kW DC fast charging (DCFC) met the needs of 100 to 200-mile range BEVs. As BEVs transition to fill long distance travel needs, the refueling times (now at 30-60 minutes for an 80% charge) will need to be far closer to that of conventional ICE vehicles. DCFC with 100 to 200 kW power levels will be required for longer range EVs and charging manufacturers have started to develop charging solutions capable of **extreme fast charging** beyond 350 kW to meet consumer expectations of an 80% charge within 15 minutes or less. Several technology gaps have been identified for XFC R&D including higher voltage batteries beyond current 400 V systems and electrical vehicle architectures that would take advantage of such higher voltages (wide bandgap [WBG] devices seem ideally suited for such applications).

Wireless charging will likely gain market acceptance due to consumer convenience and potentially lower maintenance requirements since there is no need to physically handle the charging cord and connect the vehicle to the charger. Wireless charging will also be an enabler for CAVs due to **automated charging** capability. In-motion wireless charging offers the possibility of reducing the energy storage requirement on the vehicle but requires costly roadway infrastructure upgrades. For CAVs in MaaS applications, XFC will likely be needed to meet up-time operational requirements and might also necessitate automated charging due to unmanned operation and to ensure safety.

Technical Targets & Status

Target Definition

The 2025 technical targets for the ETDS are based upon what is needed for EDVs to be competitive in performance and economics with ICE vehicles. Achieving these aggressive targets will require major technological breakthroughs through early stage research. The ability to efficiently package power electronics and electric motors across the range of vehicle types is essential to achieving high volume production and reduced U.S. petroleum consumption. The EETT metrics focus on key issues related to component cost and size to enable widespread acceptance of these vehicles. The metrics are normalized based on a component or system peak power rating into cost per kilowatt ($/kW) and power density (kW/liter).

Cost

Ultimately, EDVs 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 3 years of fuel cost savings. As part of the US DRIVE 2025 target-setting process, vehicle level modeling and simulation in Autonomie was carried out by VSATT and for EETT the result was $6/kW for a 100 kW peak power ETDS. While the 2025 target was derived based on consumer fuel savings payback expectations, EDV use in MaaS fleet applications will likely shift focus to lifetime cost and make the EDV business case more favorable.

Power Density

Power density is a very important target because of limited space “under the hood” and on the vehicle in general. Packaging constraints vary with the different vehicle types: for PHEV architectures, the ETDS must be added to a conventional ICE vehicle (i.e., a secondary drive train) as well as a high-voltage battery, DC/DC converter and on-board charger; for BEV applications, the space constraints are different, primarily driven by the large battery size and a small vehicle footprint to achieve acceptable driving range (200 miles for 2020 and more than 300 for 2025). For BEV applications, the design freedom enabled by the lack of requirements for the ICE compartment and driveline tunnel, which manufacturers typically use to expand the passenger and cargo space, further limit ETDS component packaging to around the battery, in the chassis alongside steering and suspension, and distant from vehicle crash zones. Increased power density is required to address these packaging constraints and to enable a skateboard-like chassis design that allows widespread electrification across all vehicle platforms.

Reliability

EETT’s reliability target was set to the traditional automotive life of 15 years or 150,000 miles. Longer range EVs (200+ miles) are starting to be tested in MaaS applications due to lower operating costs compared to ICE vehicles. HEVs and PHEVs are also gaining popularity in MaaS applications because they can run power accessories at “idle” without running the ICE, thereby saving on fuel costs. Some of the taxi-like MaaS applications (up to 20 hours per day of operation) can accumulate between 50,000 to 80,000 miles per year. Several automotive OEMs, including General Motors, Tesla and Volkswagen and a number of startups (i.e., Faraday Future and Lucid Motors) have indicated significant interest in EDV use for MaaS, and recent literature and analysis reports see synergy between electrification and automation. Meeting the future EETT targets by **reducing the costs and size of ETDS components would accelerate market penetration of EDVs in MaaS applications and thereby significantly increasing energy efficiency and reducing emissions** (greenhouse gas and criteria pollutants) per vehicle mile traveled**.** Mileage accumulation and therefore vehicle turnover is a lot faster for MaaS and therefore presents an opportunity for much faster and greater impact of reducing petroleum use in the transportation sector. To accommodate the extended use of EDVs, the EETT reliability requirements have been increased to 300,000 miles or 15 years.

Electric Traction Drive System Targets

The technical targets for 2025 shown in Table 2 are appropriate for all EDV applications. Historically, when the EETT emphasized HEV applications, the targets were based on a 55 kW power level. Vehicle mass has been increasing since targets were set and higher power levels are needed for full EDV applications to meet consumer vehicle performance expectations. The target includes high-voltage power electronics (one inverter and if needed a boost converter) and a single traction-drive electric motor.

Table 2. Technical Targets for Electric Traction Drive System

ETDS Targets			
Year	2020	2025	Change
Cost ($/kW)	8	6	25% cost reduction
Power Density (kW/L)	4.0	33	88% volume reduction

High-Voltage Power Electronics Technical Targets

An approximate allocation of the targets for the high-voltage power electronics is shown in Table 3. The values estimate how much can be achieved with improvements to the high-voltage power electronics and are consistent with the system-level targets. The targets in Table 3 refer to a single 100 kW PIM and a boost converter if applicable; the DC/DC converter for powering the auxiliary loads and the on-board charger have their own targets, and are not included in the table.

Table 3. Technical Targets for High Voltage Power Electronics

Power Electronics Targets			
Year	2020	2025	Change
Cost ($/kW)	3.3	2.7	18% cost reduction
Power Density (kW/L)	13.4	100	87% volume reduction

The 2025 power electronics cost and volume targets are driven by the opportunity to replace silicon switches with WBG devices which can significantly reduce the size of the power modules while enabling operation at higher temperatures and frequencies. WBG devices are significantly costlier than silicon equivalents, but enable overall power electronics cost decrease due to the system cost reductions. Secondary-level targets or more appropriately technical guidelines for advanced integrated power module (AIPM) design are included in Appendix A.

Electric Traction Motor Technical Targets

Although the technical targets have been established at the system level, an approximate allocation of the targets between the electric traction motor and the high-voltage power electronics is useful as guidance for projects that address one or the other. The values in Table 4 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.

Table 4. Technical Targets for Electric Traction Motor

Electric Motor Targets			
Year	2020	2025	Change
Cost ($/kW)	4.7	3.3	30% cost reduction
Power Density (kW/L)[1]	5.7	50	89% volume reduction

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 to optimize for vehicle efficiency, one as a motor and another as a generator, some of the architectures make use of a single machine for both purposes for cost and packaging reasons. The targets in Table 2 and Table 4 refer to a single 100 kW electric machine used for traction drive, specifically its rotor, rotor shaft, stator with ending externs, housing and cooling but not reduction gearing.

The 2025 electric motor cost and volume targets are driven by the opportunity to reduce material use with better application of existing or use of new materials to improve motor performance. Secondary-level targets or more appropriately technical guidelines for advanced electrical motor design (AEMD) are included in Appendix A.

DC/DC Converter Technical Targets

In addition to running accessories from the high-voltage bus, current PEVs require up to 3 kW of 14 V DC; the power level depends on the vehicle architecture and feature content. At a minimum, a buck DC/DC converter is required to reduce the nominal 325 V battery voltage to 14 V to power most of the accessories. The DC/DC converter is not part of the propulsion

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[1] 2020 power density target was based on 55 kW peak power at a 325 V nominal DC and resulted in 9.6 L motor volume; 2025 target is based on 100 kW peak power at a 650 V nominal DC resulting in a 2L motor volume.

system, but is an important part of electrification and increasing vehicle efficiency; therefore, it is included in the scope of EETT. In addition, some of the technical developments for DC/DC converters may be transferable to inverter designs. Table 5 shows technical targets for a 2-5 kW DC/DC converter to reduce the battery voltage from a nominal input voltage of 325 VDC to 14 V. The 2025 cost target is such that it will cost no more than the alternator that it replaces.

Table 5. Technical Targets for DC/DC Converter

DC/DC Converter Targets	2020	2025
Cost, $/kW	<50	30
Specific power, kW/kg	>1.2	4
Power density, kW/L	>3.0	4.6
Efficiency	>94%	98%

CAVs, which are planned for market introduction between 2020 and 2025, will most likely require increased low voltage power for automated driving system components (i.e., cameras, radar, light detection and ranging, central processing units). It is anticipated that DC/DC converter power requirements for CAVs will increase up to 5 kW. Future long-range PEVs (300+ miles of all electric range) will be capable of extreme fast charging at power levels higher than 350 kW resulting in much higher battery voltages (i.e., 800 VDC) placing additional requirements on the DC/DC converter.

On-Board Charger Technical Targets

All PEVs require an OBC, which converts AC input power from the EVSE (part of off-board charging infrastructure, not located on the vehicle) into DC power for the on-board battery. Table 6 shows technical targets for the OBC.

Table 6. Technical Targets for On-Board Charger

On-Board Charger Targets	2020	2025
Cost, $/kW	50	35
Specific power, kW/kg	3	4
Power density, kW/L	3.5	4.6
Efficiency	97%	98%

Wireless charging will likely become a more widespread option on future PEVs for consumer convenience (i.e., not having to plug in the cord to charge the vehicle) and as an enabling technology for CAVs in fleet use (i.e., automated charging). The vehicle receiver coil of the WPT system and the supporting power electronics components will be integrated into the OBC; however, none of these WPT system components are included in the targets presented in Table 6 since the technology is still in the R&D stage.

Many R&D gaps are currently being addressed to enable XFC beyond 350 kW to meet consumer expectations of an 80% charge within 15 minutes or less. While EETT members are actively engaged in closing the early stage research gaps associated with XFC power transfer (i.e., 800 V WBG electrical vehicle architecture), no specific targets exist since the technology is still in the R&D stage.

Current Technical Target Status

The 2017 manufacturing cost of a commercial on-road 100 kW ETDS, consisting of a single electric traction motor and inverter, ranges between $1,600 and $1,800. Of this cost, the electric motor accounts for approximately $600 to $800 and inverter about $1,000.

The 2015 EETT R&D target for the ETDS was $12/kW which was met for a 100 kW peak power ETDS based on the U.S. Department of Energy (DOE) Vehicle Technology Office co-sponsored industry and national laboratory R&D efforts. Table 7 shows comparison of 2025 ETDS technical targets with current on-road technology status and 2015 EETT R&D technical targets. Significant cost reductions are required, 50% compared to 2015 EETT R&D target and 67% compared with current on-road technology, to meet the 2025 EETT R&D target of $6/kW. Significant size reductions are also required to increase the ETDS power density as the system peak power remains at 100 kW. To meet the 2025 EETT R&D target, the power density must be increased by more than 800 percent compared to 2015 EETT R&D technical targets and 450 percent compared to current on-road technology.

Table 7. Comparison of Current Status with 2025 Technical Targets for ETDS

ETDS Targets	On-road Status	2015 R&D Target	2025 R&D Target	2025 vs. On-road	2025 vs. 2015
Cost, $/kW	18	12	6	-67%	-50%
Power density, kW/L	6	3.5	33	+450%	+843%

Table 8 presents the same comparison as above for power electronics and electric motors.

Table 8. Current Status and 2025 Technical Targets for Power Electronics and Electric Motors

	On-road Status	2015 R&D Target	2025 R&D Target	2025 vs. On-road	2025 vs. 2015
Power Electronics					
Cost, $/kW	10	5	2.7	-67%	-34%
Power density, kW/L	18	12	100	+455%	+733%
Electric Motors					
Cost, $/kW	8	7	3.3	-59%	-53%
Power density, kW/L	9	5	50	+455%	+900%

Figure 7 represents the 2015 target inverter cost breakdown by major contributing part based on the technical cost modeling conducted by ORNL assuming high-volume production (100,000 units per year); similar information is presented for electric motor in Figure 8. Inverter cost assessment is based on information from the Delphi High Temperature Inverter DOE funded project[2]. The electric motor information is based on the ORNL High-Power Density Ferrite Permanent Magnet Motor project[3]. For the inverter, the power module represents nearly 40% of the total costs in large part due to the cost of the silicon IGBT switches. For the electric motor, the stator with copper windings and rotor with magnets each represent nearly 40% of the total cost. Electric motor cost is almost solely materials based by the amount and cost of copper wire, steels and permanent magnets.

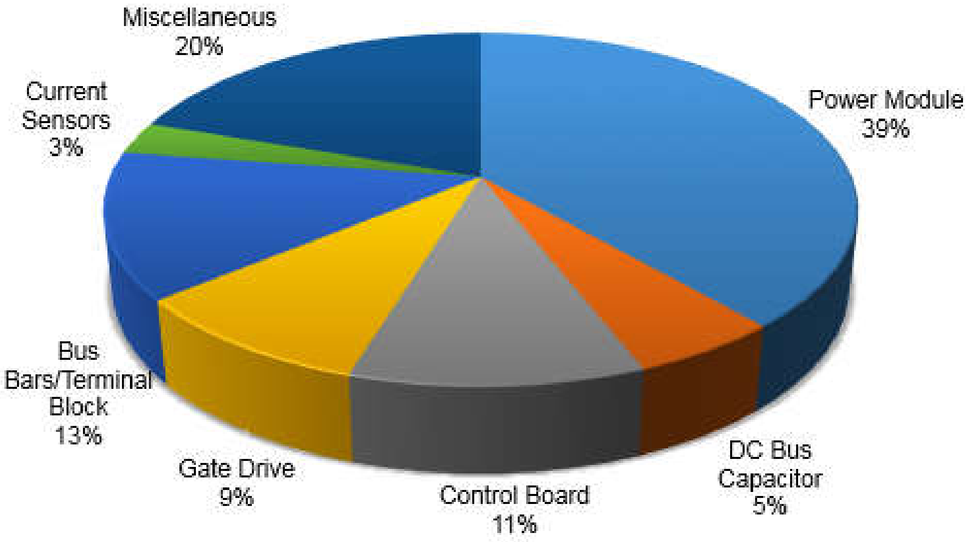

Figure 7. High Voltage Power Electronics Cost Status (2015 EETT target)

Source: Oak Ridge National Laboratory

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[2] FY2013 Annual Progress Report for the Advanced Power Electronics and Electric Motors Program

[3] 2016 U.S. DRIVE Highlights of Technical Accomplishments Overview Report

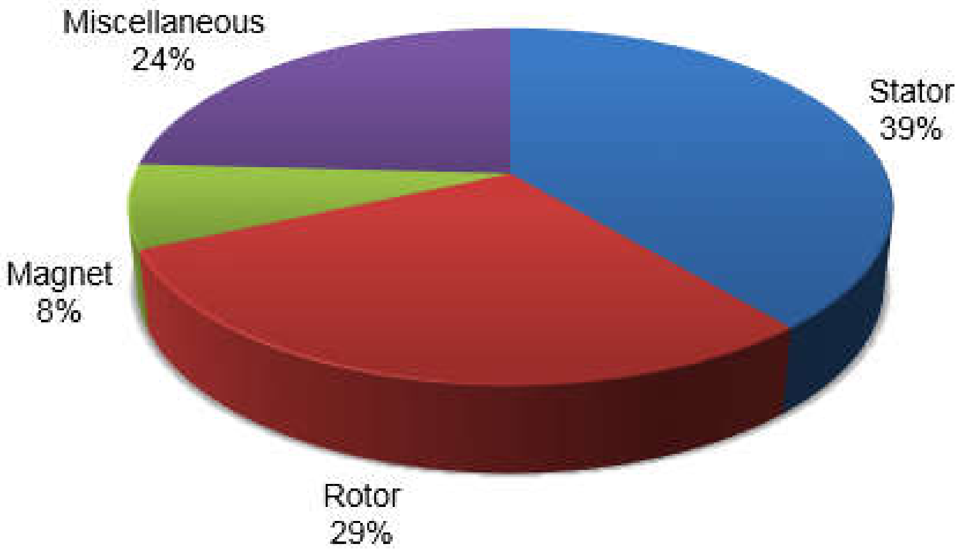

Figure 8. Electric Motor Cost Status (2015 EETT target)
Source: Oak Ridge National Laboratory

Gaps and Barriers to Reach 2025 Technical Targets

Cost and size are the key barriers to achieving the EETT 2025 ETDS technical R&D targets and increased EDV market penetration. The cost needs to be cut in half and size reduced by an order of magnitude (Table 7), and power and reliability need to be doubled (82% peak power increase to 100 kW and 100% reliability increase to 300,000 miles) to meet the 2025 targets.

According to industry input, the following high-level technology gaps need to be filled to achieve 2025 cost and size reduction targets:

a) OEM driven:
  - 100kW and greater WBG inverters to double the power
  - Multi-physics integration of power electronics to cut size in half
  - Non-rare-earth machines as insurance policy against rare-earth magnet price volatility
  - Improved materials (i.e., copper, steel) to cut costs in half and double reliability

b) Supplier driven:
  - Understanding of system-level trade-offs (i.e., cost/performance impact of material substitution)
  - Understanding of standard tests and requirements so they can leverage their knowledge base to help develop technical solutions

Reduction in the volume of the components is necessary to enable ETDSs to fit within the increasingly smaller spaces available on the vehicle. Motor volume reduction is limited by the flux density capabilities of materials used in current electric steels and the electrical conductivity limitations of copper windings. Power electronics volume is currently driven by stand-alone sub-components and the available passive components. The potential of WBG devices to change design constraints has become a critical factor in driving size and efficiency improvements. This, along with continued power electronics integration and simplification with the necessary multi-physics improvements is needed for meeting the targets.

Power Electronics

Technical barriers for power electronics are:

- **WBG device power and voltage levels and availability**. The commercially available WBG devices are not ready for use in automotive qualified 800V+ and 100 kW ETDS.
- **WBG multi-physics integration designs to enable optimal use**. While current power electronics designs can be tailored to accommodate WBG devices, they do not fully utilize WBG high voltage, high temperature and frequency capabilities. WBG devices are more costly than traditional silicon devices, therefore it is important to maximize their potential through multi-physics integration to reduce the overall system costs.
- **High temperature and isolation materials**. WBG devices themselves are capable of withstanding high junction temperatures, but the temperature tolerances of surrounding layers, materials and interfaces need to be increased to achieve the goal of compact, high-performance WBG-based components.

To address the power electronics barriers, R&D is needed to close the following technical gaps:

- Higher power and high voltage WBG device availability
- Development of a domestic supply chain
- Component optimization for miniaturization and cost reduction. Low inductance requirements for WBG multi-physics integration indicate a short path which causes thermal management challenges. Thermo-mechanical reliability is also an important consideration. High-performance materials with high-temperature capabilities will be important.

Electric Motors

Electric motor specific barriers are:

- Magnet cost and rare-earth element price volatility
- Non-rare-earth electric motor performance
- Material property optimization (e.g., isolation, conductivity)

Most production ETDS use permanent magnet (PM) motors which contain NdFeB magnets. These magnets account for 20 to 30 percent of the total electric motor costs in today's production systems. This is in large part due to the high prices of heavy rare-earth elements (neodymium and dysprosium) which are needed to prevent demagnetization at high temperatures. While the heavy rare-earth prices have come down substantially and remained stable since the 2011 spike (Figure 9), there is still significant price volatility concern as today's designs will drive the vehicles to be commercialized in 4 years. China continues to dominate the rare earth market, accounting for more than 90 percent of production. The long-term market demand is strong and the only domestic source of rare earth elements (Mountain Pass mine) closed after rare earth prices started to decrease. This puts the U.S. permanent magnet motor market (and others) in a precarious position.

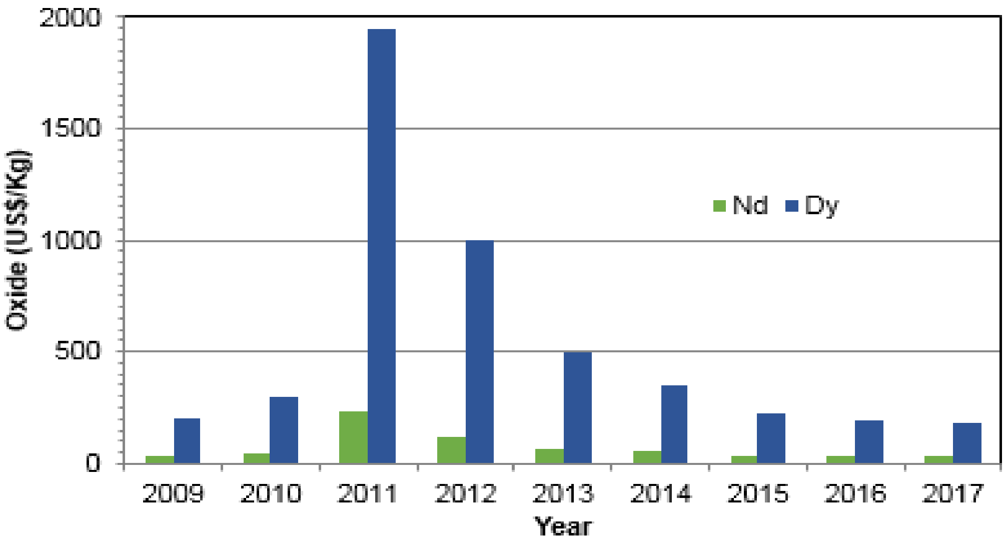

Figure 9. Rare Earth Metal Prices Track Oxides Very Closely
Source: Metal Pages courtesy of Critical Materials Institute

To address the electric motor barriers, R&D is needed to close the following technical gaps:

- Reduced rare-earth magnet content and elimination of heavy rare earth elements
- Development of non-rare-earth magnets and machine designs optimized for them. Significant improvements are needed in non-rare-earth magnet motor packaging to meet volume constraints.
- New and improved materials to lower cost and improve performance and reliability. Examples include silicon steel, ultra-conductive copper, and improved thermal materials (i.e., improved enamels for higher voltage and motor potting).
- Advanced cooling/thermal management techniques to reduce size, cost and improve reliability.

Strategy to Overcome Barriers and Achieve Technical Targets

The chosen strategy to overcome current barriers and achieve the technical targets is to conduct R&D with industry input aimed at achieving a significant technology push. DOE national laboratories are working with the supply base to improve WBG-based power electronics and non-rare earth or magnet-less electric motors to meet the 2025 ETDS R&D targets. Component targets and material requirements have been identified and reviewed with suppliers. Supplier-based solutions have been encouraged as the national laboratories focus on early-stage research to close the technical gaps in knowledge and on conducting system and component tradeoffs. This will result in basic technology building blocks to be used as inputs for automotive OEM advanced development groups. OEMs will provide guidance by reviewing requirement development and conducting design reviews. Program status is evaluated in relation to the technical targets on an annual basis.

Power Electronics Strategy

Power electronics technical gaps include: availability of large WBG devices, domestic supply chain, and optimization for miniaturization and cost reduction. To address these gaps the main R&D strategy includes WBG device manufacturer engagement, supplier industry engagement, and component miniaturization to increase vehicle applications to reduce cost through production scale. WBG device manufacturers can be engaged through DOE and industry co-sponsored development projects, through national laboratory testing and evaluation, and by developing and publishing guidelines or requirements for device manufacturers. Supplier industry engagement could take the form of soliciting their input to advance innovation and in return provide them technical guidelines to align their R&D investments with EETT goals. Miniaturization could be achieved by researching board-based power electronics (planar construction integrating bus structure, capacitor, and module substrate), full utilization of emerging device capabilities, utilizing ultra-conducting copper as a key enabler, and use of high-performance computing to accelerate innovation.

Potential R&D pathway for meeting 2020 cost target of $3.3/kW and 13.4 kW/L:

- Deconstruction of traditional component boundaries and simplification
- Component integration

Potential R&D pathway for meeting 2025 cost target of $2.7/kW and 100 kW/L:

- Multi Physics Integration
- Additional component integration
- Device application
    - Characteristics of full automotive operating range
    - Optimal operating strategies and in-board device fabrication

The resulting inverter component breakdown cost and percentages showing largest cost contributors are shown in Table 9 and Figure 10.

Table 9. Potential Cost Pathway to Meeting 2025 Power Electronics R&D Cost Target
Source: Oak Ridge National Laboratory

Inverter Component	Cost
Power Module	$59
DC Bus Capacitor	$38
Control Board	$37
Gate Drive	$60
Bus Bars/Terminal Block	$26
Current Sensors	$11
Miscellaneous	$39
Total	**$270**

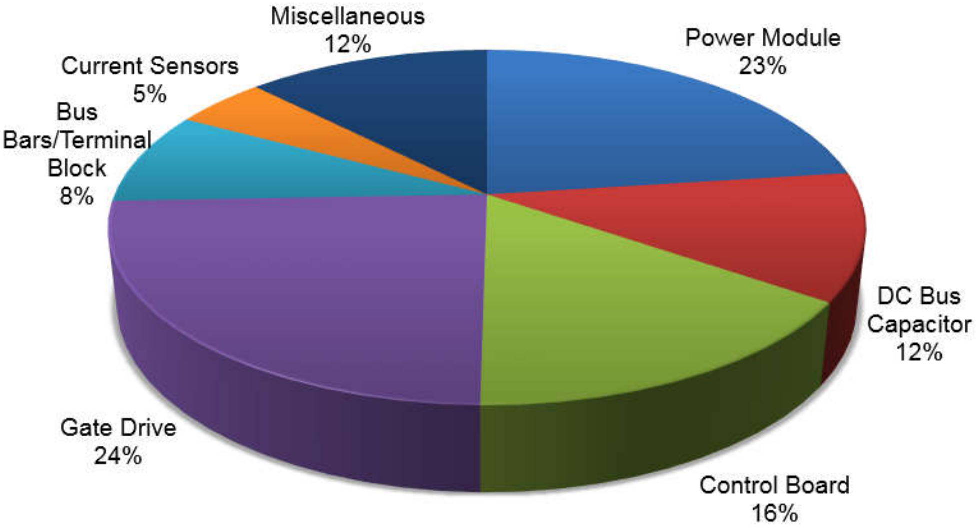

Figure 10. Inverter Cost Breakdown for a Potential Pathway to Meeting 2025 Target
Source: Oak Ridge National Laboratory

Power Electronics R&D Areas

To carry out the power electronics strategy for meeting the 2025 targets, specific research is needed in many areas to address the underlying issues. Figure 11 presents the power electronics R&D areas and the following text describes the background and issues to be addressed for each one.

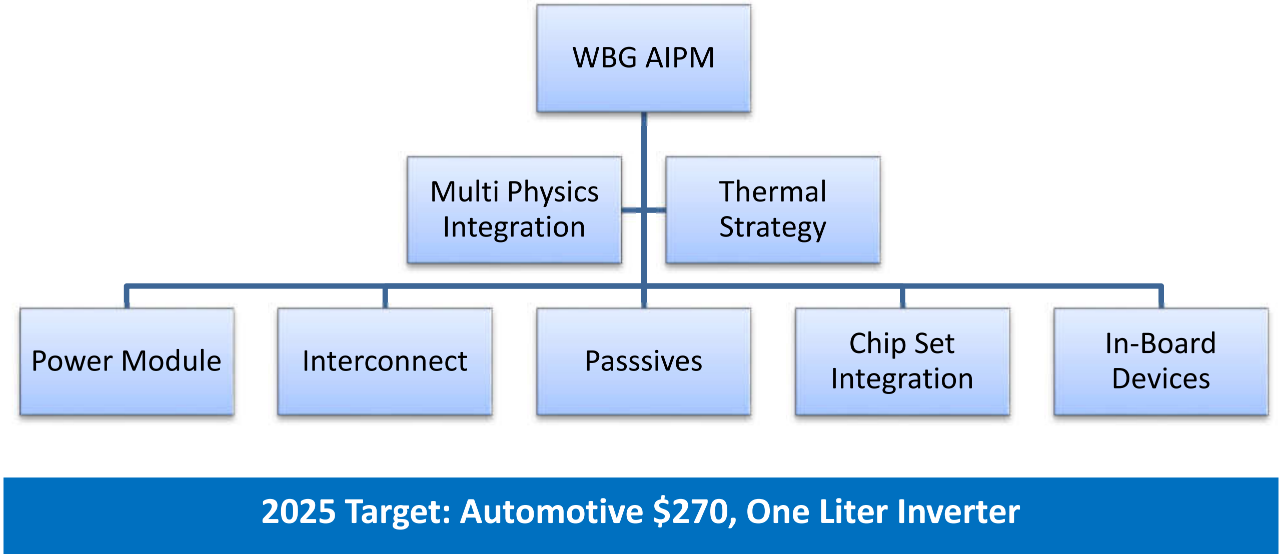

Figure 11. Power Electronics R&D Areas

Multi Physics Integration

Background: Traditional two-dimensional packaging is cost effective and allows for larger distances between sub components providing for noise and thermal isolation. The downside of long electrical pathways are higher parasitic resistance and inductance as well as more material use. It also requires integration of multiple structure types and results in a complex assembly.

Issues to be addressed: Common structure, simple design, electrical and thermal isolation, and heat management.

Thermal Strategy

Background: Traditionally a heatsink is mounted to the power module. There have been a few instances of double-sided cooling based on localized power module heat sink cooling. The disadvantages of current approaches include: packaging limitations; reduced cooling effectiveness of capacitors, gate drive, and controllers; limited vehicle placement, and bulky designs.

Issues to be addressed: Compatibility with common vehicle thermal strategies and effectiveness without decreasing vehicle system efficiency. Highly conductive thermal materials that are electrically isolated and cost effective are needed.

Power Module

Background: Traditional packaging typically provides a relatively cost-effective construction. Disadvantages are: package inductance; material stack ups; and the need for a large heatsink.

Issues to be addressed: Higher switching frequencies will require lower inductance to reduce device voltage requirements. Higher temperatures enable downsizing but create thermo-mechanical issues. Need to address interfaces with the next layer. Thermal management system needs to be more effective without increased complexity to increase packaging densities.

Passives

Passive components typically represent one of the largest costs of the power electronics, and they also account for a major portion of the volume and weight. Materials that offer improved dielectric properties, and higher temperature capabilities are needed to reduce the overall volume. For example, Polymer-film capacitors are used in most EDVs today, but they currently cannot tolerate sufficiently high temperatures for future applications that will require 150 degrees Celsius (°C). Many current polymer-film capacitors are typically 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.

Capacitors

Background: Smoothing out voltage and current in a switched power supply is critical. Consistent performance over the temperature operating range, high energy density, low equivalent series resistance, and graceful failure are required. Disadvantage of current capacitor technology are high temperature operation (above 105°C) and limited energy density.

Issues: Introduction of WBG and need to reduce the length of electrical pathways requires smaller DC bus capacitor that can be highly integrated with the switching devices and capable of operating at higher temperatures.

Inductors

Background: Inductors store energy to stabilize output current in power converters for constant current output during operation. With gate drive and power supply in inverter, inductors can be much smaller and are less of a focus for inverters compared to converters where the inductor is the main part of the power stage. Critical factors in performance are core and copper losses, thermal management, core materials and aging effects.

Issues to be addressed: Highly dense power electronics will limit the ability to remove heat. This will require better materials to reduce losses and size, along with improved thermally conductive material and thermal management techniques. Compared to capacitors, in terms of materials, there is less development opportunity for inductors (nano-crystalline could be but is expensive for the automotive market; ultra-conducting copper would help reduce the size of the inductor).

Transformers

Background: Transformers provide isolation and step up/down voltage or current. Like inductors, their application is in gate drivers and also in on-board chargers. Critical factors include: coupling issues, self-capacitance, leakage inductance, and common mode EMI.

Issues to be addressed: Transformers are large and heavy. Higher switching frequencies enabled by WBG switches will require better isolation and elimination of voltage and current oscillations. Higher operating temperatures are expected and will require improved thermal solutions.

In-Board Devices

Background: As power electronics power modules become smaller the ancillary circuits need to be reduced in size. An opportunity exists to integrate resistors, capacitors, and inductors into a printed circuit board through forming or embedding.

Issues to be addressed: Voltage and power ratings need to be increased. Improved materials and manufacturing processes are needed to transition from discrete parts to board-integrated parts.

Chip Set Integration

Background: Gate drive chip set area has become larger than the power module. A symmetrical low inductance gate drive to power module interconnect is needed particularly with use of WBG switches.

Issues to be addressed: Board area for ancillary circuits needs to be reduced as power module size and need for fast ancillary circuit response increases. Particular considerations need to be given to gate drive chip sets. These include: sufficient gate drive capability; high noise immunity capability; high temperature capability; cross-talk mitigation; short-circuit protection; voltage spike suppression.

Electric Motors Strategy

Identified technical gaps for electric motors include: reduced rare-earth magnet content (no heavy rare-earth metals), non-rare-earth magnets, non-rare-earth optimized machines and advanced materials. To address these gaps, the main R&D strategy is to reduce cost by using new materials with improved capabilities and performance, and applying them in motor design innovations. Materials with improved capabilities and performance include ultra-conducting copper, heavy rare-earth-free and non-rare-earth magnets, and low-cost, high-voltage insulating materials. These material improvements are applicable to many different electric motor types as shown in Figure 12 with designs suitable for EDVs listed in red at the bottom of the figure. Understanding new material properties and their application to improve motor performance is key to apply them in motor design innovations. Electrical and thermal improvements of 30 to 50 percent could be achieved through analytical understanding, more accurate modeling, and optimization of motors enabled by high-performance computing.

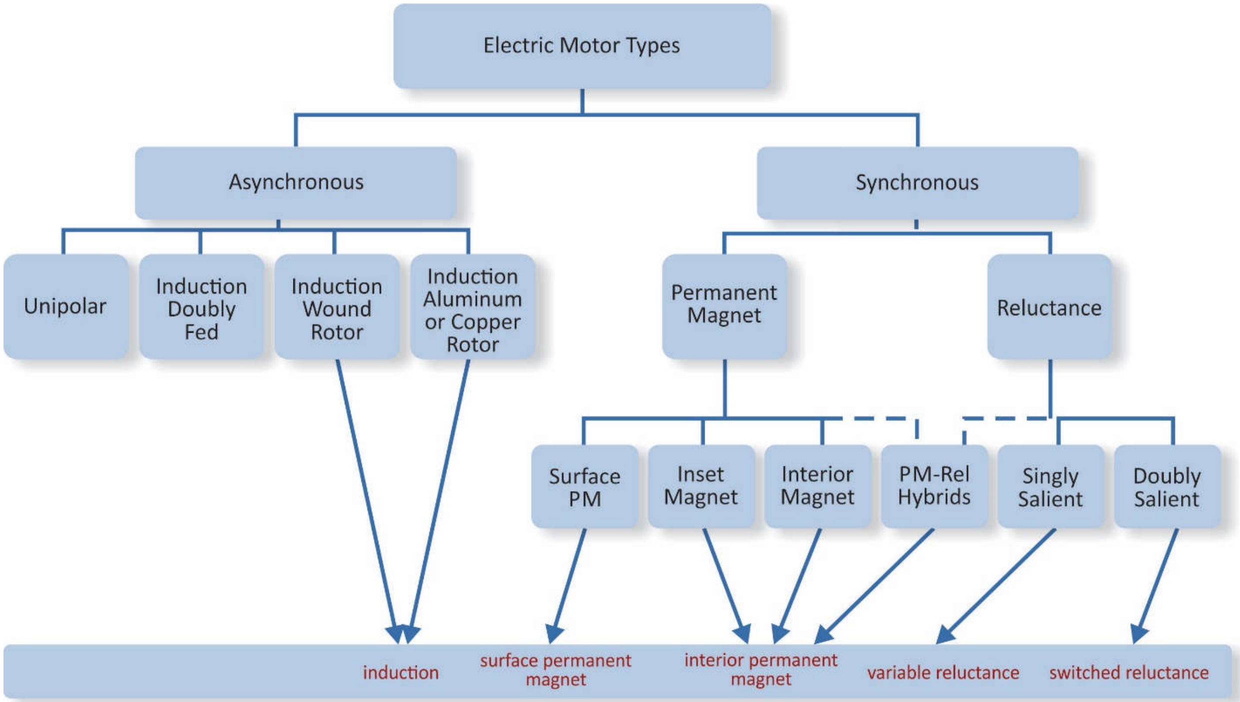

Figure 12. Electric Motor Types

Potential R&D pathway for meeting 2020 cost target of $4.7/kW and 5.7 kW/L:

- Materials development and understanding their impacts on motor design and performance (design and long-term characteristics)
- Electrical steel: properties and the impact of manufacturing processes (i.e., stamping), and methods of mitigating property changes due to manufacturing processes. Low-cost, high-efficiency steel.
- Non-rare earth magnet material development and its application

Potential R&D pathway for meeting 2025 cost target of $3.3/kW and 50 kW/L (in addition to the steps required to meet the 2020 targets):

- 2nd generation of carbon-nanotube-based copper materials and their application (design & long term characteristics)
- Replacement of magnets with soft magnet materials

The resulting electric motor component breakdown cost and percentages showing largest cost contributors are shown in Table 10 and Figure 13.

Table 10. Potential Cost Pathway to Meeting 2025 Electric Motor R&D Cost Target
Source: Oak Ridge National Laboratory

Electric Motor Component	Cost
Stator	$154
Rotor	$78
Magnet	$13
Miscellaneous	$85
Total	**$330**

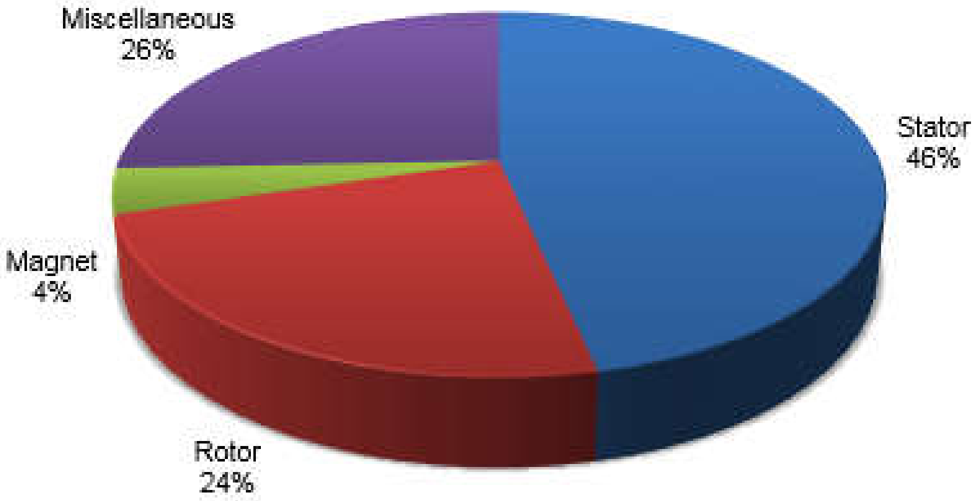

Figure 13. Electric Motor Cost Breakdown for a Potential Pathway to Meeting 2025 Target
Source: Oak Ridge National Laboratory

Electric Motor R&D Areas

To carry out the electric motor strategy for meeting the 2025 targets, specific research is needed in many areas to address the underlying issues. Figure 14 presents the electric motor R&D areas and the following text describes the background and issues to be addressed for each one.

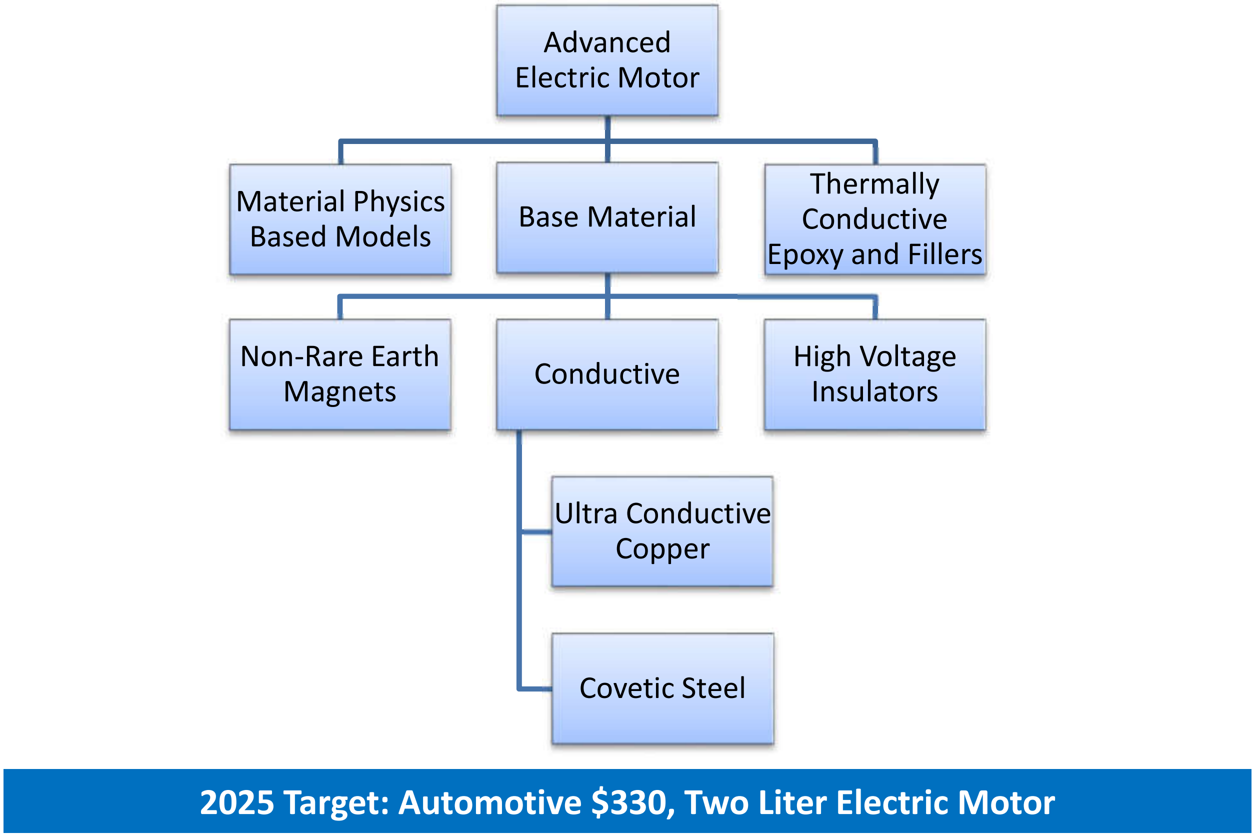

Figure 14. Electric Motor R&D Areas

Material Physics Based Models

Background: Basic understanding of magnetic properties of materials exists, but a more accurate understanding would allow for higher-power density machines. Factors influencing magnetic properties are stamping effects and stacking factor with new lamination techniques.

Issues to be addressed: Magnetic properties vary within a single sheet of material. Residual stresses from stamping or cutting prevent magnetic properties from being homogeneous, which limits the optimization of the electric motor design. New lamination strategies (i.e., in-die bonding or coated steels) can also result in changes to stacking factor.

Base Materials

Background: Material conductivity thermally drives the amount of material necessary to create the required magnetic field to create mechanical power. This defines a given power motor size. Additionally, as electric vehicle propulsion systems increase in voltage, the need for improved, low-cost insulators that meet automotive durability are needed.

Issues to be addressed: Material performance characterization techniques are not well known or identified in the literature. Improved electrically and thermally conductive materials are needed for size and cost reduction to occur in electric motors. Electrical insulators are needed in the 1,200 V range that are cost effective and have an operational life equivalent to 300,000 vehicle miles.

Non-Rare-Earth Magnets

Background: Current PM motors use neodymium iron boron PMs because of their superior magnetic properties. However, these magnets are expensive and their prices are unstable. 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.

Issues to be addressed: Non-rare earth magnetic materials that possess magnetic properties similar to NdFeB magnets but cost less and have higher temperature limits are needed.

Conductive Material

Background: Material's electrical and thermal conductivity drive the amount of material needed to create the necessary magnetic field to create mechanical power. This defines motor size for a given power level.

Issues to be addressed: Copper and steel that have higher electrical and thermal conductivity are needed to reduce the size and cost of electric motors.

High Voltage Insulators

Background: High instantaneous rate of voltage change (dV/dt) occurs in WBG inverters. As ETDS increase in voltage, better insulators that meet the automotive durability and cost requirements are needed.

Issues to be addressed: Improved enamels and varnish systems are required to assist the motor survive 300,000 vehicle miles due to high dV/dt from WBG inverter switching.

Existing insulation systems will break down much faster than in current low voltage motors (300 V). There is very little motor industry experience in high dV/dt environments and no current research to address motors driven by WBG devices.

Thermally Conductive Epoxy, Fillers, and Winding Insulation

Background: Conventional motor packaging materials (epoxies, fillers, winding insulation, slot liners) can often pose a significant resistance to heat removal from the motor.

Issues to be addressed: It is important to reduce the thermal resistance of the motor packaging stack-up to help with increasing the power density, reduce footprint and cost of the motor while maintaining good reliability. There is a need to increase the thermal conductivity and reduce contact resistances of several elements in the motor packaging stack-up—thermally conductive epoxies, fillers, as well as winding insulation materials. These will have significant impacts across a wide range of high-performance motor types and configurations.

Appendix A – Wide Bandgap Advanced Integrated Power Module 2025 Technical Guidelines

Requirement	Current State-of-Art (WBG)	AIPM (Nominal)	Scalability
Peak power (kW)	**30**	**100**	**200**
Continuous power (kW)	15	55	110
Voltage rating (V)	900 – 1,200	900	1,200
Maximum device current (A)	100	200	200
Device metallization			
Top	NO	NO	YES
Bottom	YES	YES	YES
Maximum junction temperature (°C)	180	250	250
Isolation (kV)	3	3	3
Battery operating voltage (Vdc)	325 (200 – 450)	650 (525 – 775)	975 (850 – 1,100)
Switching frequency capability (kHz)	30	30 – 50	30 – 50
Power factor		> 0.6	> 0.6
Maximum current (A)		600	800
Precharge time – 0 to 200 Vdc (seconds)		2	2
Maximum efficiency		> 97	> 98
Torque ripple (%)		NA	
Output current ripple – peak to peak (%)		<= 5	TBD
Input voltage & current ripple (%)		<= 5	TBD
Current loop bandwidth (kHz)		2	2
Maximum fundamental electrical frequency (Hz)		2,000	2,000 (depends on the motor speed)
Ambient operating temperature (°C)		-40 to +125	-40 to +125
Storage temperature (°C)		-50 to +125	-40 to +125
Cooling system flow rate, maximum (lpm)	10	10	10
Maximum particle size for liquid cooled (mm)	1	1	1
Maximum coolant inlet temperature (°C)	85	85	85
Maximum inlet pressure (psi)		25	25
Maximum Inlet pressure drop (psi)		2	2

Requirement	Current State-of-Art (WBG)	AIPM (Nominal)	Scalability
Useful life (years/miles)	15/150,000	15/300,000	15/300,000
Minimum isolation impedance-terminal to ground (M ohm)		1	1
Minimum motor input inductance (mH)		0.5	0.3
Target cost ($2.70/kW) @ 100K/units	**$732**	**$270**	**$540**
Volume (@100kW/l)	**5 liters**	**1 liter**	**2 liters**
Mass (@50kW/kg)	**6.25kg**	**2.00 kg**	**4.00 kg**

Assumption: 8 Pole Motor

Gate Drive Requirements for SiC Based Systems

	Current State-of-Art	100 kW	200 kW
Galvanic isolation	Yes (cap > 10pF)	Yes (cap < 10pF)	Yes (cap < 10pF)
High sinking and sourcing current (A)	+/- 20	+/- 30	+/- 30
Active miller clamping/crosstalk suppression	No	Yes	Yes
Under voltage lockout (UVLO) function	Yes	Yes	Yes
Thermal protection function	No	Yes	Yes
Short circuit protection function	Yes (response time > 2 µs)	Yes (response time > 2 µs)	Yes (response time > 2 µs)
Soft turn-off function for short circuit protection	Yes	Yes	Yes
Support both zero and negative voltage	Yes (-6 V/ 20 V)	Yes (-10 V / 20 V)	Yes (-10 V / 20 V)
Temperature Range (°C)	-40 to +85	-40 to +200	-40 to +200
Board Dimensional Footprint	68 mm x 135 mm	187.5 mm x 80 mm	187.5 mm x 80 mm

*Note gate drive temperature estimates by NREL to run at 183°C to 205°C using SiC junction temperature of 250°C

Appendix B – Non-Heavy Rare Earth Advanced Electric Motor Design 2025 Technical Guideline

Requirement	Current State-of-Art	AEMD (Nominal)	Scalability
Peak power (kW)	**30**	**100**	**200**
Continuous power (kW)	15	55	110
Torque (Nm)		300	400
Maximum speed (rpm)		≤20,000	≤20,000
Battery operating voltage (Vdc)	325 (200 – 450)	650 (525 – 775)	975 (850 – 1,100)
Switching frequency capability (kHz)	30	30 – 50	30 – 50
Power factor		> 0.8	> 0.8
Maximum current (A)		600	800
Precharge time – 0 to 200 Vdc (seconds)		2	2
Maximum efficiency (%)		> 97	> 98
Torque ripple (%)		5	5
Output current ripple – peak to peak (%)		<= 5	TBD
Input voltage & current ripple (%)		<= 5	TBD
Current loop bandwidth (kHz)		2	2
Maximum fundamental electrical frequency (Hz)		2,000	2,000 (Depends on the motor speed)
Ambient operating temperature (°C)		-40 to +125	-40 to +125
Storage temperature (°C)		-50 to +125	-40 to +125
Cooling system flow rate, max (lpm)	10	10	10
Maximum partial size for liquid cooled (mm)	1	1	1
Maximum coolant inlet temperature (°C)	85	85	85
Maximum inlet pressure (psi)		25	25
Maximum Inlet pressure drop (psi)		2	2
Useful life (years / miles)	15 / 150,000	15 / 300,000	15 / 300,000
Minimum insulation impedance-terminal to ground (M ohm)		20	20
Minimum motor input inductance (mH)		0.5	0.3
Target Cost ($3.30/kW) @ 100K/Units	**$448**	**$330**	**$660**
Volume (@50 kW/l)		**2.0 l**	**4.0 l**
Mass (@5kW/kg)		**20 kg**	**40 kg**

Appendix C – ORNL Testing and Evaluation Data on 2016 BMW i3

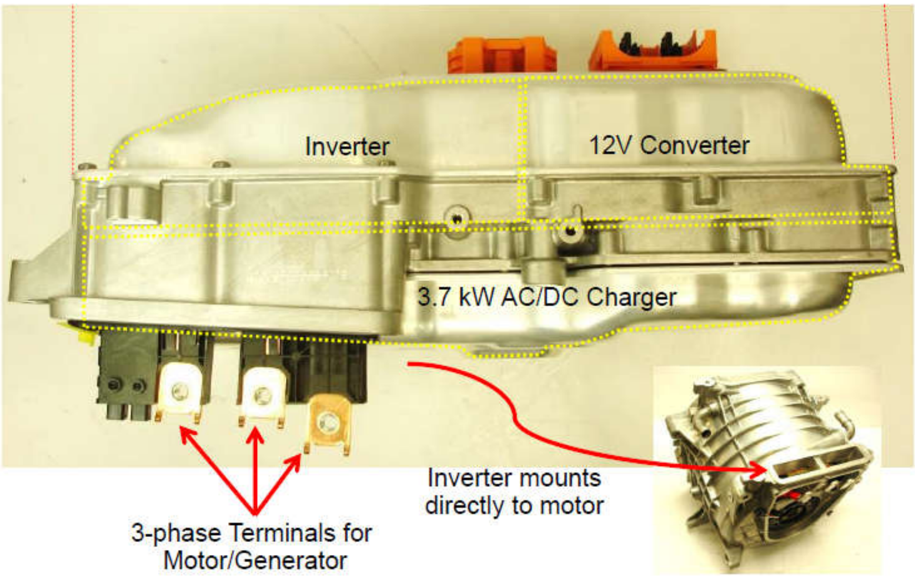

Figure C-1. 2016 BMW i3 Inverter Assembly Including 12V DC/DC Converter and AC/DC Charger
Source: Oak Ridge National Laboratory

Table C-1. 2016 BMW i3 Inverter Component Weights
Source: Oak Ridge National Laboratory

2016 BMW i3 Inverter Component	Weight (kg)
Dc bus capacitor	0.94
Dc capacitor cover	0.30
DSP board	0.37
Gate drive board	0.27
3-phase busbar	0.54
IGBT module	1.31
Snubber module	0.06
HV DC Circular busbar	0.03
EMI shield above gate drive board	0.22
EMI shield above DSP board assembly	0.09
Metal IGBT cover	0.13
Main connectors and support frame	1.35
Top aluminum casing	0.23
Long bolts (6) for IGBT	0.06
AC/DC charger and its cooling plate	0.66
Mid-housing section with cooling channels	2.32
Total inverter	**8.81**

Specific Power of 14 kW/kg

Table C-2. 2016 BMW i3 Inverter Component Volume

Source: Oak Ridge National Laboratory

2016 BMW i3 Inverter Component	Volume (L)
Power/Signal connectors	0.36
Top Compartment (Control, inverter and dc/dc)	3.44
Housing Mid Cooling system	2.24
AC bus bar housing	0.73
Total inverter	**6.77**

Power Density of 18.5 kW/L

Table C-3. 2016 BMW i3 Electric Motor Specifications

Source: Oak Ridge National Laboratory

Parameter	BMW i3
Power	125 kW
Torque	250 Nm
Weight	42 kg
Stator mass	20.8 kg
Rotor mass	14.2 kg
Stator OD	242 mm
Stator ID	180 mm
Stator Stack Length	132 mm
Stator core mass	13.7 kg
Copper mass	7.1 kg
Magnet mass	2.0 kg
Active Volume (stack only)	6.1 L
Volume (including cooling jacket)	13.6 L

Specific Power 3 kW/kg and Power Density of 9.2 kW/L

Figure C-2. 2016 BMW i3 Electric Motor (External View [top right and left], Rotor [bottom left], and Stator with Cooling Channels [bottom right].

Source: Oak Ridge National Laboratory

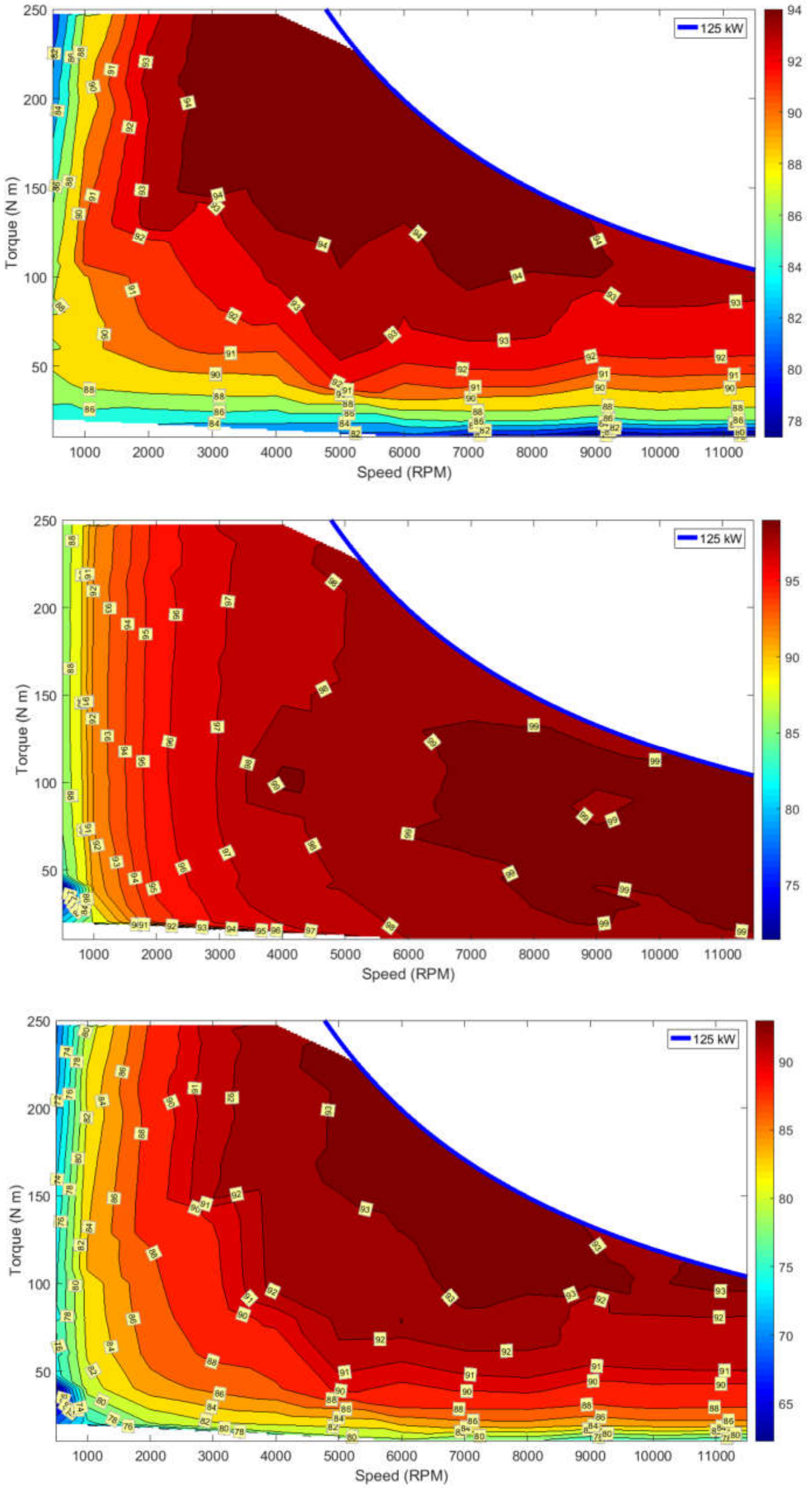

Figure C-3. 2016 BMW i3 Electric Motor (top), Inverter (middle) and Combined System (bottom) Operating Efficiency Maps.

Source: Oak Ridge National Laboratory