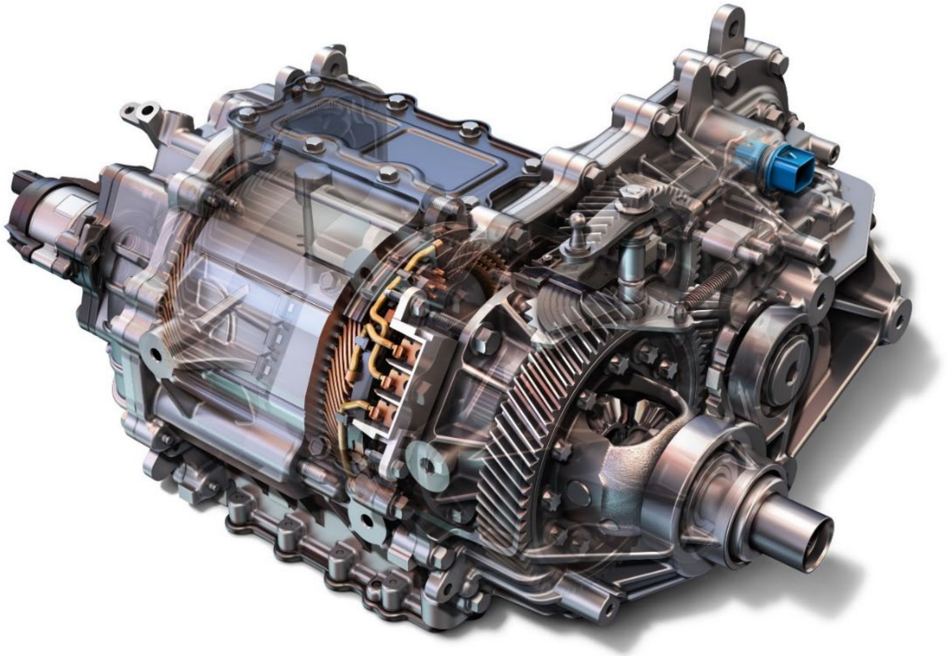
USDRIVE

DRIVING RESEARCH AND INNOVATION FOR
VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Electric Drive
Technical Team Roadmap

March 2024



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 Stellantis, 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).

Electric Drive Tech Team is one of 12 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) needs have grown significantly since the last Roadmap in 2017. Battery electric vehicles (BEVs) applications have grown as the energy storage cost has declined and the recognition of the compelling cost of ownership that can be achieved for fleet operators. There are vehicles 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 4 years, this drastic improvement in vehicle electrification has coincided with a radical transformation in the vehicle marketplace. What we have seen, especially in the last few years, is a radical shift that is driving electrification. The changes we have seen are as follows:

1. Electrified vehicles are moving past just being economy boxes to appeal to broader market tastes of the consumer.
2. The electrification of larger vehicles (i.e., Pickup Trucks, SUV's) is increasing the opportunity to leverage high-volume, high-power components into medium and heavy-duty vehicles.
3. Supply chain issues will continue to impact technology choices for the foreseeable future.
4. The desire to support development of electrification from US-based suppliers, from low level all the way to Tier 1.
5. A significant increase in the recycling of BEVs.

These trends require that ETDS design evolves rapidly to achieve and maintain commercial success. The systems must continue to decrease cost to achieve cost of ownership equal to or less than that of ICEs vehicles. Power levels need to increase to accommodate the growing number of vehicle applications. Durability needs to be better understood and evaluated to ensure the viability of electrification in fleet applications. The efficiency of the overall drive cycle needs to be improved to reduce the amount of energy storage required on the vehicle. Finally, given the significant role electrification will be playing in our future, the ability to recycle all of the materials effectively will be critical. Achieving this will require an overall systems and ecosystem view to address and resolve the 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 vision of a decarbonized, environmentally responsible on-road transportation, charging and fueling infrastructure system throughout the United States that is affordable and resilient.

Additionally, emphasis recently has been increased on manufacturability and recycling and coordination of light duty vehicle efforts with 21st Century Truck Partnership (21CTP) partners for medium and heavy commercial vehicle application. The vision highlights the commitment to creating the proper value proposition for electrification for everyday consumers.

It is important to note that the gaps of electrification are still substantial when considering the goal of affordable EV's. For example,

1. Large-area SiC devices is limited mainly by defects in the substrates – while these have improved dramatically over the years, they are still not at the level of purity of Si substrates.
2. Scaling GaN HEMTs (High-Electron-Mobility Transistors) on Si presents challenges, particularly in increasing current and scaling voltage breakdown. This involves scaling in lateral and vertical directions, akin to SiC. However, vertical GaN devices face substrate improvement challenges.
3. Reliance on foreign sources exists with GaN, rare-earths, magnetic steels, and other elements that make up the electric drive.

By diversifying the supply base and technological options for vehicle OEMs it will maximize cost stability and minimize disruption in vehicle production.

This roadmap was developed collaboratively through an iterative process to ensure it represents a united vision of industry and government stakeholders. The Electric Drive Technical Team (EDTT) Original Equipment Manufacturers (OEM) partners were actively involved in the update of targets looking at 2025, 2030, and 2035. Technology gaps such as the critical needs for more efficient and reliable wide-bandgap devices, for high-performance motor materials that utilize available components to produce maximum energy density, for component integration based on multi-physics co-design principles to optimize drive motor system design, and for the 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 rare earth (RE) magnets without heavy RE, non-RE, or magnet-less (e.g., induction) electric motors of innovative designs to meet the ETDS R&D targets. Along with these advanced motor designs, 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 such as sustainable high-performance motor materials (permanent magnets, soft magnets, and winding conductors), multi-physics integration, and vertical GaN devices. This early-stage research will close the technical gaps in knowledge, enabling better drive train system and component tradeoffs to be made (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.

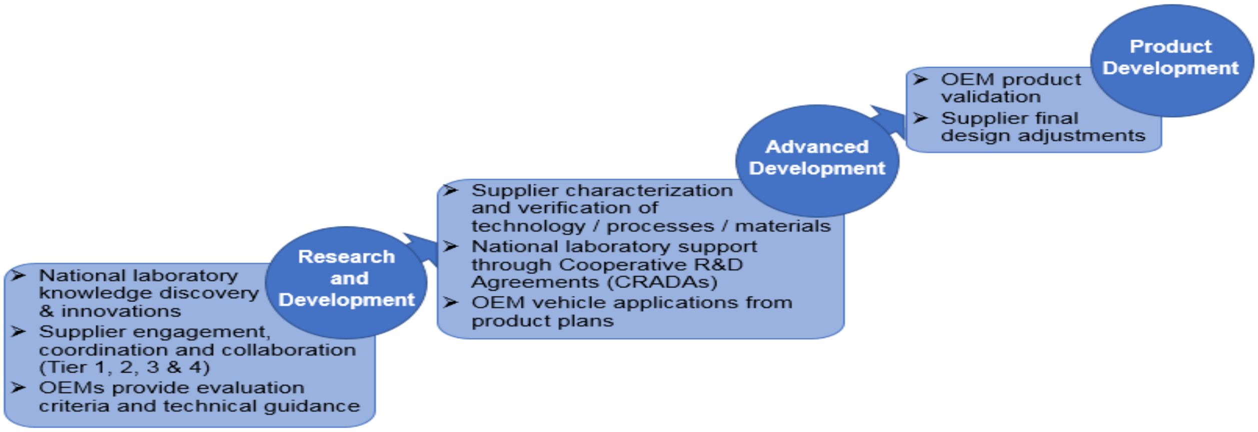


Figure ES-1. Automotive Product Development Cycle

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Acronyms

21CTP	21st Century Truck Partnership
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
EDTT	Electric Drive 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
SME	subject matter expert
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 Electric Drive Technical Team (EDTT) 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 EDTT mission supports U.S. DRIVE's Vision that "A decarbonized, environmentally responsible on-road transportation, charging and fueling infrastructure system throughout the United States that is affordable, equitable, and resilient." It also directly supports U.S. DRIVE's Mission to "accelerate decarbonization through pre-competitive, innovative, and affordable light-duty vehicle-related technologies and energy infrastructure to enable the transition to a sustainable transportation-energy system." EDTT has laid out the following mission to support the U.S. DRIVE's Mission:

- Support the mass market adoption of electric drive vehicles
- Accelerate the development of cost-effective and compact Electric Traction Drive Systems (ETDS) that meet Department of Energy (DOE) Targets
- Enabling electrification across all light-duty vehicle types and collaborating with the medium and heavy-duty vehicle efforts to speed technology deployment across transportation

The focus areas are E-Motors, Power Electronics, and Electric Traction Drive System. The design, technology, cost, and reliability of each are the key fundamental elements. Targets that have been set reflect the transition of electric vehicles from a limited envelope of type to full adoption across the entire range of vehicle types. The Partnership Research Targets for the electric traction drive are as follows*:*

- *2025 - $4.00/kW for a 150kW system*
- *2030 - $3.00/kW for a 200kW system*
- *2035 - $2.67/kW for a 225kW system*

Targets are based on the following assumptions:

- Power levels are peak power for 30 seconds
- System voltage level is 600V for 2025, moving to 800V by 2030
- Reliability requirement of 15 years/300,000 miles
- Targets based on annual production volume of a million units
- Gearbox is not included

Transformational change is needed to achieve the targets to solidify vehicle electrification over the entire market not just in the United States, but globally. Those ETDSs that provide greater system efficiency at the key operating points (drive cycle dwell points), provide greater control, better packaging, are more reliable, and are cost effective will be the market leaders.

Scope

The EDTT 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:

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

The variety of electric traction implementations are still needed to address diverse global markets. Depending on the vehicle type and system architecture, other power electronics besides the inverter might also be included and are covered by the EDTT, 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 EDTT's scope.

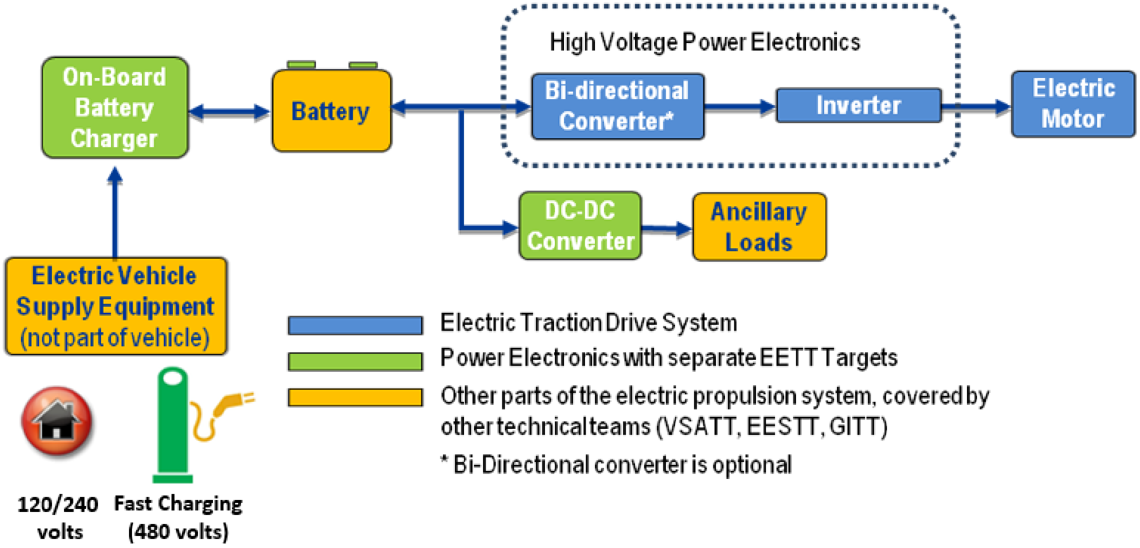

Figure 1. Components of Generic ETDS

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 EDTT targets. In the case of wireless power transfer (WPT) or extreme fast charging (XFC) vehicle capability, the EDTT is responsible for all related power electronics components on the vehicle as well as interfaces to the off-board components necessary for their operation. It is important to note that in the US, 80% of EV charging happens at home.[1] For research related to WPT and XFC, EDTT coordinates efforts with the Grid Interaction Tech Team (GITT).

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, and Electrochemical Energy Storage Tech Team (EESTT). The EDTT 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 EDTT 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 EDTT R&D focused on HEVs, but the focus has shifted to fully electric drive vehicles, which include PHEVs, EREVs, BEVs and FCEVs. Full EDV system layouts are shown in Figure 2.

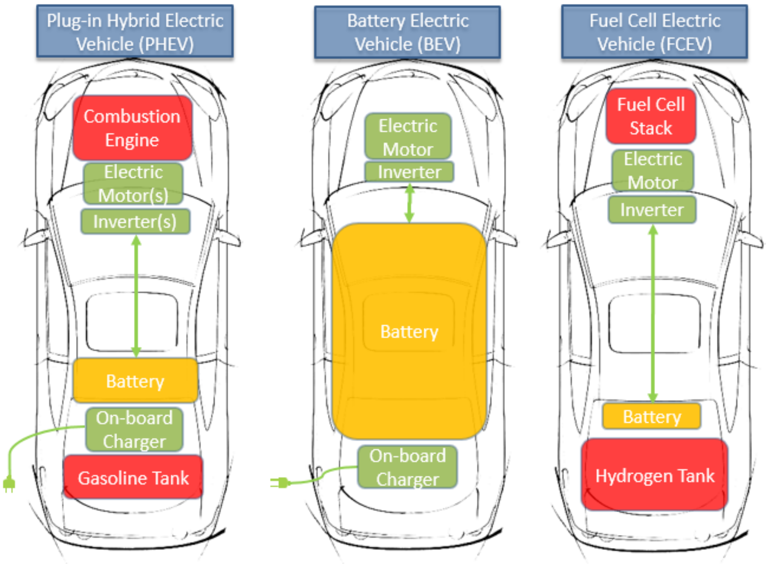

Figure 2. EDV Architecture Layouts

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[1] Christopher Mims, “The Electric-Car Revolution Needs More Plugs,” Wall Street Journal, February 27-28, 2021,

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) is growing fast but has not reached the level of adoption one might expect given the interest level, as shown in Figure 3. Vehicle OEMs have made significant pledges to electrify all their light-duty vehicle offerings. Broadening the type of electrified vehicles offered will be a big factor in making the technology broadly accepted. Wide market adoption hinges on an attractive value proposition being delivered across the socio-economic spectrum. New technology often faces an adoption curve like that depicted in Figure 4. After innovators and then early adopters, history shows that one often sees periods of chasm that refer to a disconnect between market offerings and consumer needs and expectations. Demand stays stagnant until such a time that the new technology becomes viable for the next broader market segment. The sustainability/wide-spread-adoption of the technology is dependent on it creating the appropriate value proposition across the entire market. This is also illustrated in Figure 5 showing the current differences in market utilization of electrification technology compared to others, when serving broad market needs.

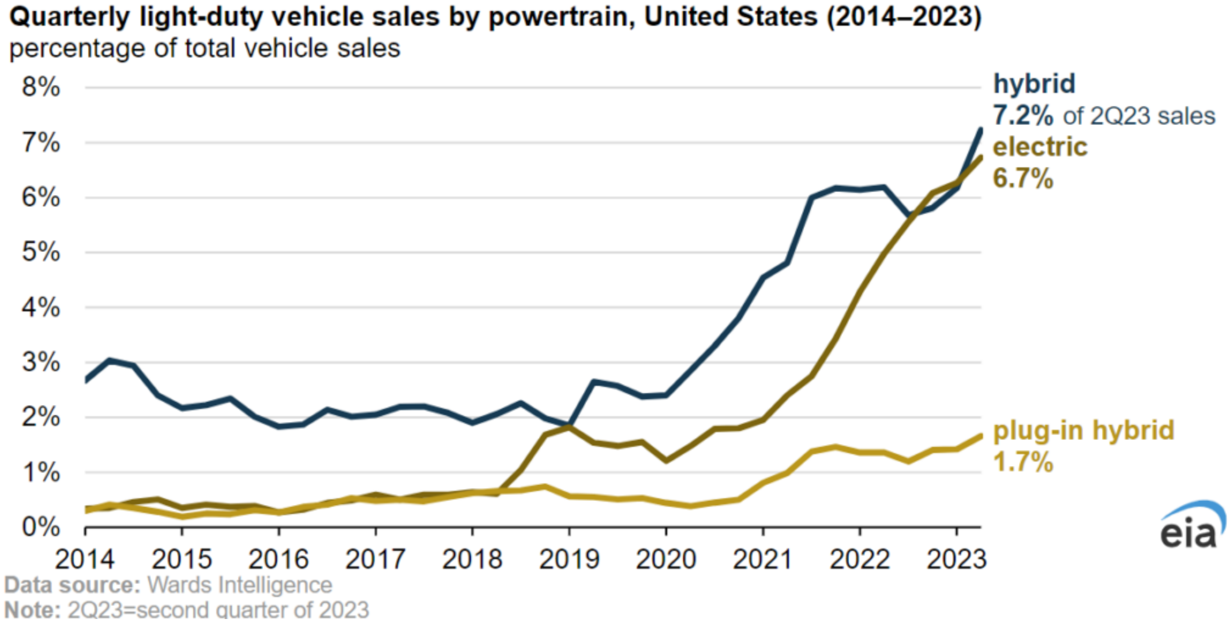

Figure 3. US EV (BEV & PHEV) Share of New Vehicle Sales: 2015 - 2021

Source: [Electric Vehicle Sales and Market Share (US - Updated Monthly) - CarEdge]()

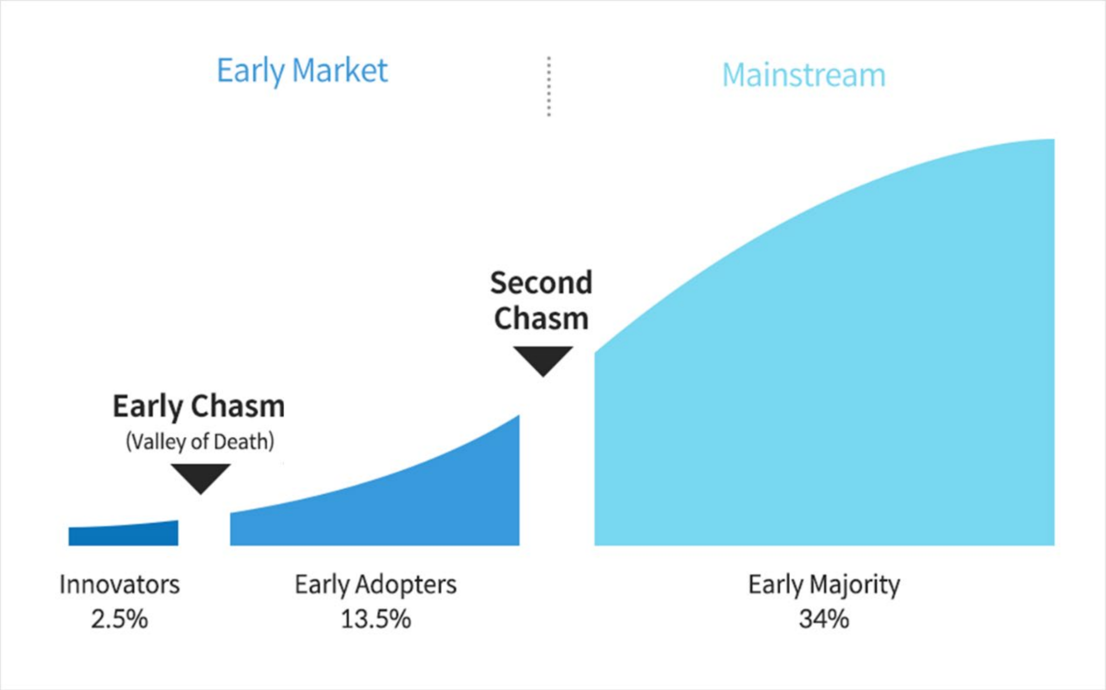

Figure 4. Technology Chasm (based on Crossing the Chasm, Geoffery A. Moore)

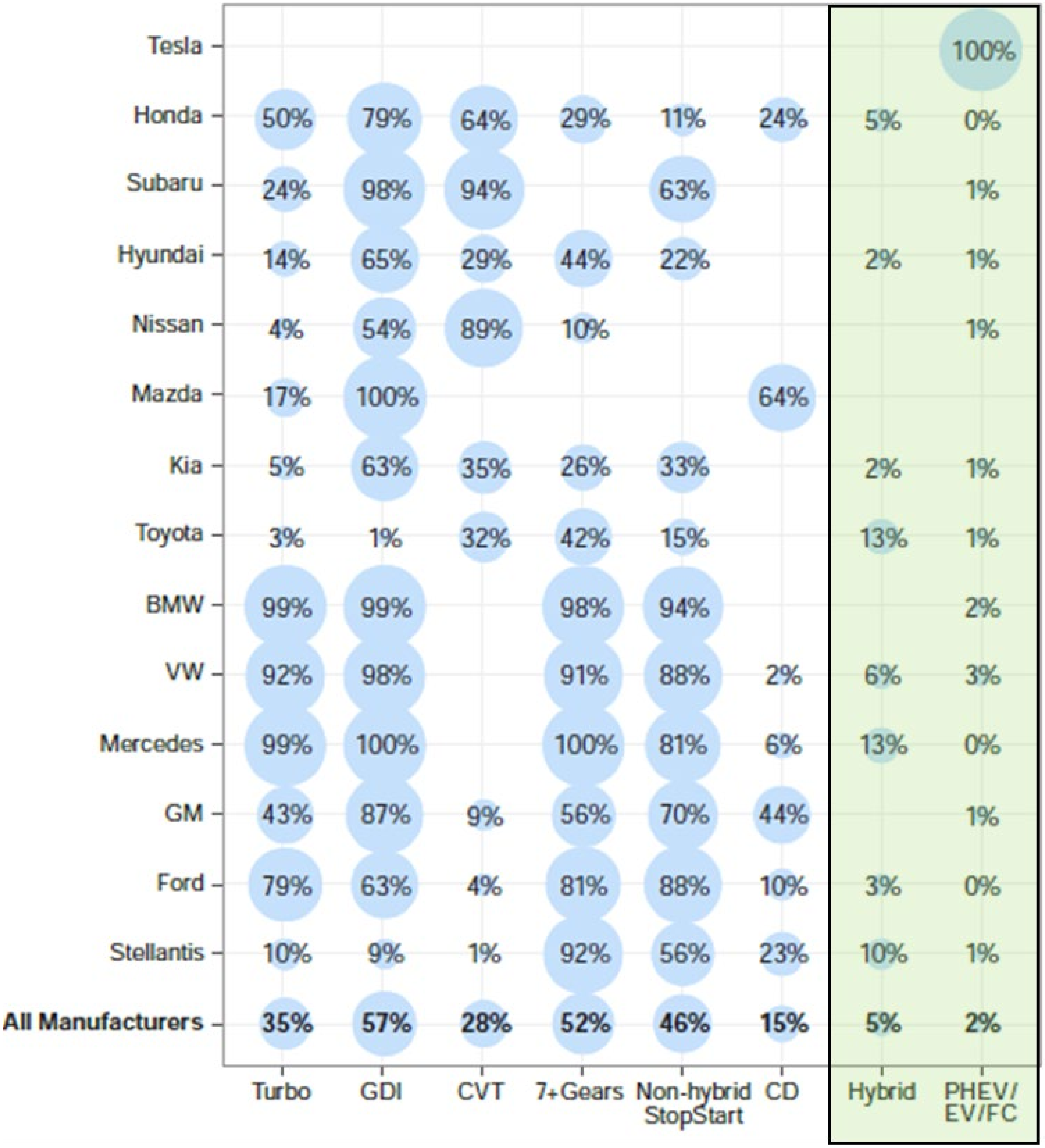

Figure 5. Manufacturer Use of Emerging Technologies for Model Year 2020, Shaded Region Shows Electrified Propulsion

Source: U.S. Environmental Protection Agency, 2021 EPA Automotive Trends Report, EPA-420-R-21-023, November 2021.

The EDTT focus since the 2017 Roadmap has been on 100kW systems versus previous targets based on a 55kW peak power level. Again, the EDTT has reevaluated power level targets. Several factors are influencing power level requirements. EV trucks and SUVs weigh 2.5 times more than ICE trucks and SUVs. In terms of sedans, the EVs weigh about 30% more than ICE cars. The change in mix of vehicles and type of EV's being offered.[2] Typical EV's back in 2017 were a small passenger vehicle such as the Chevrolet Bolt 1669kg (3680lb) and Fiat 500e 1395kg (3075lb). Now we are seeing EVs such as GMC Hummer 4200kg (9259lb) and Rivian R1S 2650kg (5842lb). Vehicle mix has continued to change with consumer taste and vehicle performance expectations, shown in Figure 6 and Figure 7, driving the need for even higher power systems. We can see from Figure 8 that vehicle propulsion power has continued to increase over time driven by the mix of vehicles and consumer performance expectations. Table 2 shows the average propulsion power MY20 for each of the USDRIVE partners. All these factors have driven the EDTT peak **power level targets** to be increased in 2030 and 2035. Voltage levels are also being increased from 600V to 800V in 2030 to reflect the improvements in battery technology.

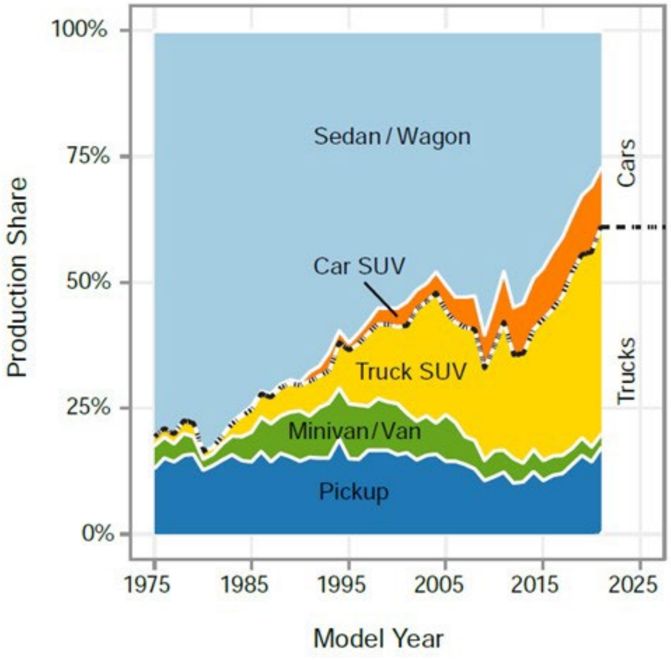

Figure 6. Production Share of Vehicle Type

Source: U.S. Environmental Protection Agency, 2021 EPA Automotive Trends Report, EPA-420-R-21-023, November 2021.

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[2] Keith Tomatore, "The True Ramifications of EV vs. ICE," Perficient, April 5, 2023, https://blogs.perficient.com/2023/04/05/the-true-ramifications-of-ev-vs-ice/.

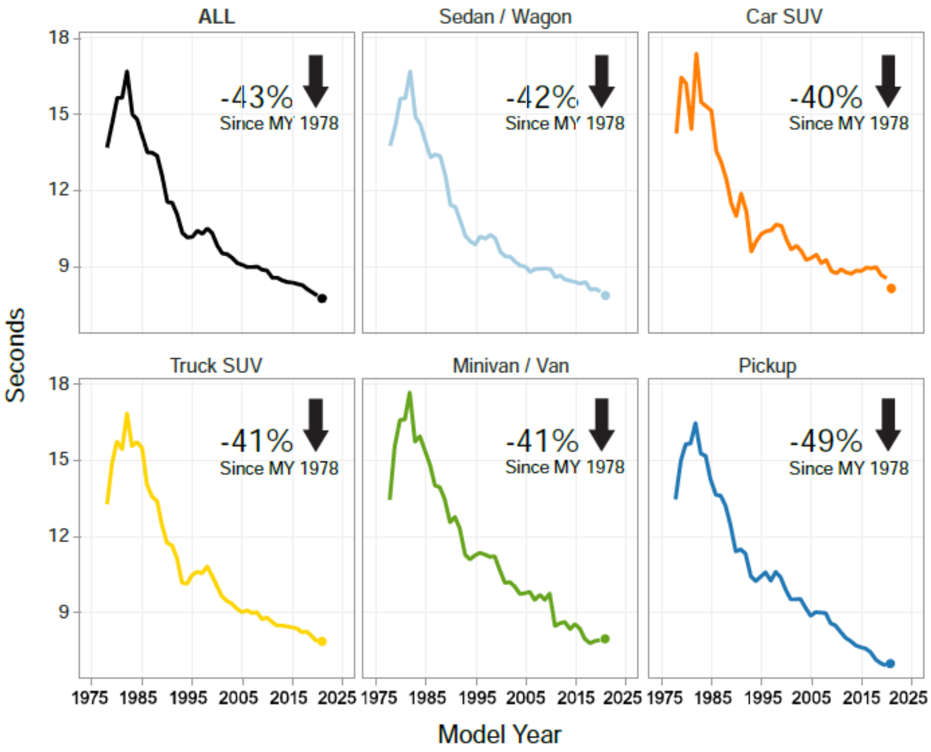

Figure 7. Calculated 0-60 Time by Vehicle Type

Source: U.S. Environmental Protection Agency, 2021 EPA Automotive Trends Report, EPA-420-R-21-023, November 2021.

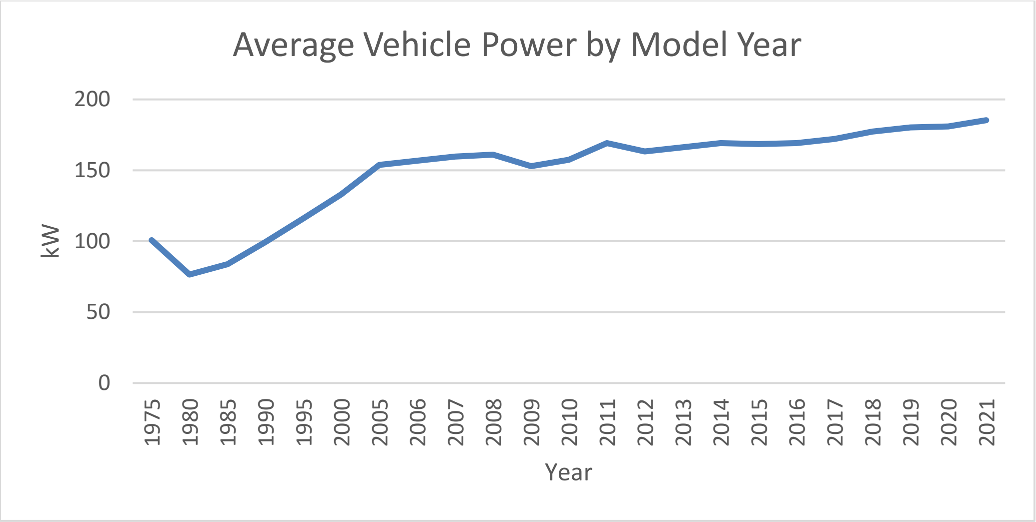

Figure 8. Vehicle Power by Year.

Source: U.S. Environmental Protection Agency, 2021 EPA Automotive Trends Report, EPA-420-R-21-023, November 2021.

Table 2. MY 2020 Average rated Vehicle Propulsion Power

Vehicle Manufacturer	kW
Ford	213
General Motors	195
Stellantis	217

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[3] cost of energy storage has been significantly reduced since the first EDV model introductions in 2010, and we are now seeing larger battery packs being placed in the vehicles. EV's pack sizes in 2015 typically would be around 60kWh and today we are seeing 100kWh becoming more common. As larger vehicle types are electrified, we will continue to see battery pack size increase beyond the largest pack sizes available today of 135 kWh and 200 kWh in the near future based on recent announcements. Mass of these vehicles are going up, increasing traction drive power and efficiency requirements.[1] 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 under current market forecast of 10 percent by 2025 and 30 percent by 2030 as suggested in Figure 9 will be difficult. But, if we consider administration goals of 50 percent by 2030, the urgency of technical innovation is even more imperative.[4] 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.

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[3] John Voelcker, "EV's Explained: Battery Capacity, Gross Versus. Net, "Car and Driver April 10, 2021

[4] Joseph R. Biden Jr., "Executive Order on Strengthening American Leadership in Clean Cars and Trucks," The White House August 5, 2021

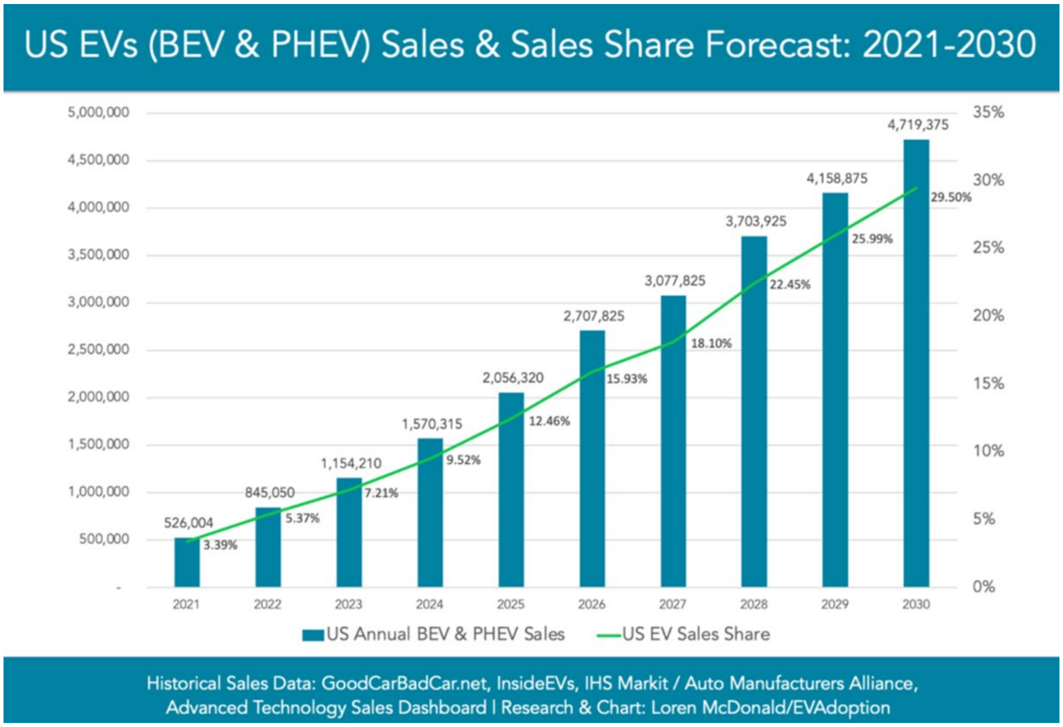

Figure 9. Projected EDV Sales

Source: EVADOPTION, https://evadoption.com/ev-sales/ev-sales-forecasts/

Future Trends

BEVs offer an attractive platform for connected and automated vehicle (CAV) developers due to the design freedom that a modular skateboard chassis architecture allows (see example in Figure 10). Many manufacturers aim to launch CAVs in mobility-as-a-service (MaaS) applications (e.g., car-share, ride-share, ride-hailing) in the next 5 years due to their lower operating costs have been delayed as the complexity of the technology becomes better understood. But MaaS continues to be seen as a transformer of the vehicle value proposition. MaaS perspective changes requirements 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 has been set to **300,000 miles** for 2025.

Automakers that are developing long-range (> 300 mile) 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 ETDS cost targets for 2025 and prior were based on 500,000 units annual manufacturing volume, for 2030 and beyond targets, the unit volume assumption has been increased to **1,000,000 units**.

Figure 10. Examples of Skateboard Chassis Containing Electric Powertrain for passenger and trucks.

As BEVs transition to fill long-distance travel needs, the refueling times (now at 30-60 minutes for an 80% charge with DC Fast Charging) will need to be far closer to that of conventional ICE vehicles. DC Fast Charging (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** (XFC) greater than 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 electric vehicle architectures that would take advantage of such higher voltages (wide-bandgap [WBG] devices seem ideally suited for such applications).

Wireless charging, in a recent study, found that 96% of those surveyed would like access to wireless charging - making wireless charging more desirable than vehicle autonomy. This is an important aspect of driving consumer convenience and improving the value proposition of EV's.[5] This could likely lead to greater 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. The challenges of wireless charging are mainly safety and producibility, Electromagnetic interference, heat generation, and metal foreign object detection.

In-home charging will be the predominant location of vehicle charging. As vehicle energy storage increases, the need to provide higher power along with greater convenience is needed. Wireless charging as mentioned above will certainly be the method of automatically connecting the vehicle to the grid to charge and discharge when needed. Higher power levels will be needed to ensure an acceptable level of power transfer to provide adequate vehicle range.

Materials for drive motors with stable cost and ability for high rpm operation due to the emerging trends to increase power density and total efficiency of EDT. Motor materials must be capable of upscaling in use by factor of ten times to permit full EV adoption. Higher operation RPM (14,000 to 20,000 to 40,000?) of drive motor is effective way to boost motor power density without greater use of materials for motor construction. Both permanent magnets with high energy density and soft magnets with low losses must be used, but current magnetic material options are not capable of use in this greatly expanded use scenario or at this greatly increased RPM scenario.

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[5] Autovista24, "Wireless EV Charging – a gimmick or a revolution?" August 22, 2022

Technical Targets & Status

Target Definition

The technical targets for the ETDS are based upon what is needed for EDVs to be competitive in performance and economics with ICE vehicles. The targets recognize the need to provide solutions that enable all vehicle segments to be addressed by providing a better value proposition to consumers. Providing consumers with a better value proposition will ensure market adoption. Achieving these aggressive targets will require major technological breakthroughs through early-stage research. In order to establish U.S. industry as a leader in electrification, it is critical that this early-stage research can be translated into competitive advantages for industry in the U.S. The technical breakthroughs need to focus on those technologies that can be best taken advantage of by a highly skilled and capitalized industrial base. Consumers want to see vehicles that are more usable, functional, and cost effective to operate. This translates into high-density packaging of power electronics and electric motors, high drive cycle efficiency, reliability, and cost effectiveness. Accomplishing this will come from creating new materials and enabling higher orders of integration to occur from in-situ fabrication. The EDTT 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, the purchase price of EDVs should be comparable to ICE vehicles, but also be able to provide greater value to the consumer. The cost targets in this roadmap allow for a small initial 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 ISATT (Integrated Systems Analysis Tech Team), and the collection of inputs from SMEs (Subject Matter Expert) in Power Electronics and Electronic Machines. The result was a target of $4/kW for a 150kW peak power ETDS being set.

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

Previous EDTT's reliability targets were 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/fleet 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 Ford, Stellantis, General Motors, Tesla and Volkswagen and a number of startups have indicated significant interest in EDV use for MaaS/Delivery, and recent literature and analysis reports see synergy between electrification and automation. Meeting the future EDTT targets by **reducing the costs and size of ETDS components would accelerate market penetration of EDVs in MaaS/Delivery 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/Fleet; hence, it presents an opportunity for much faster and greater impact of reducing petroleum use in the transportation sector. This is the primary reason for the EDV EDTT reliability requirement of 300,000 miles or 15 years being adopted.

Technical Targets Needed for Full Market Adoption and Creating Competitive Advantage

Future of Targets

Targets have been the basis of metrics to guide research and component development and establish the basic tipping point for electric propulsion to be viable. These metrics have been in existence for over 25 years and helped guide electric vehicles to where they are today. Given the progression of the EV market, the U.S. generally has high operating cost and must lead through innovation to be competitive in electrification. Innovation must provide differentiators that consumers find of value, such as safety, Miles per Gas Gallon Equivalent (MPGe), driving enjoyment, portable power, and end-of-vehicle-life value. For example, significant opportunity for improvement of MPGe exist when accounting for the traction system performance over the whole drive cycle. This can be illustrated by reviewing Tesla's MPGe rating from 97.1 MPGe in 2015 to over 119.1 in 2020. While multiple factors contribute to this improvement, drive cycle efficiency is a key contributor. The EDTT assessed on-the-road drive cycle efficiency (e.g., US06) for electric vehicles moved from the MPGes of 70's to the 80's over those same years. Additionally, if a drive cycle efficiency improvement of 5% can be obtained, it would have a meaningful impact on reducing battery needs and the overall vehicle cost and range.

Value Proposition

Improving the value proposition provided to the consumer and fleet operator is at the heart of driving the adoption of EVs. Electrification of the propulsion system - besides providing clean transportation - can provide greater control yielding greater performance, efficiency, and safety than incumbent technology. This leads the EDTT to identify and evaluate new functions or capabilities that have the potential to create value and what new performance metrics need to be established.

Recyclability

The ETDS contains materials that are rare or come from areas of the world that may or may not continue to be available to the United States. Therefore, recapturing those elements and ensuring the appropriate disposal of other materials is critical for wide market adoption of the technology.

Electric Traction Drive System Targets

The technical targets for 2025 shown in Table 3 are appropriate for all EDV applications. The targets are progressively increased starting at 150kW in 2025 and increasing until the year 2035. This is to accommodate the addition of new vehicle types and their associated requirements. The target includes high-voltage power electronics (one inverter and if needed a boost converter) and a single traction-drive electric motor.

Table 3. Technical Targets for Electric Traction Drive System

ETDS Targets			
Year	2025	2030	2035
Power Level kW (Peak)	150	200	225
Voltage	600	800	800
Cost ($/kW)	4	3	2.67
Power Density (kW/L)	50	66	75

High-Voltage Power Electronics Technical Targets

An approximate allocation of the targets for the high-voltage power electronics is shown in Table 4. 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 power inverter 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 4. Technical Targets for High-Voltage Power Electronics

Power Electronics Targets			
Year	2025	2030	2035
Power Level kW (Peak)	150	200	225
Voltage	600	800	800
Cost ($/kW)	1.80	1.35	1.20
Power Density (kW/L)	150	200	225

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 to 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

The technical targets have been established for the electric traction motor. The values in Table 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.

Table 5. Technical Targets for Electric Traction Motor

Electric Motor Targets			
Year	2025	2030	2035
Power Level Kw (Peak)	150	200	225
Voltage	600	800	800
Cost ($/kW)	2.20	1.65	1.47
Power Density (kW/L)	75	100	112.5

Certain motor designs may have an impact on the weight, volume, and cost of other parts of the vehicle. Many hybrid vehicle architectures require two electrical machines to optimize 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 3 and Table 5 refer to a single electric machine used for traction drive, specifically its rotor, rotor shaft, stator with end windings, housing and cooling, but not the 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 and efficiency. Additional consideration is needed to account for extreme expansion (10X) of materials usage in the scenario of near-full adoption of EV vehicles. 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 5 kW at 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 system but is an important part of electrification and increasing vehicle efficiency; therefore, it is included in the scope of EDTT. In addition, some of the technical developments for DC/DC converters may be transferable to inverter designs. Table 6 shows technical targets for a 7.5 kW DC/DC converter to reduce the battery voltage from a nominal input voltage of the vehicle to 14 V. The 2025 cost target is such that it will cost no more than the alternator that it replaces.

Table 6. Technical Targets for DC/DC Converter

DC/DC Converter Targets	2025	2030	2035
Cost, $/kW	30	20	16.67
Specific power, kW/kg	4	6	6.25
Power density, kW/L	4.6	6.8	7.5
Efficiency	>98%	98.5%	98.5%

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) and thus 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 7 shows technical targets for the OBC.

Table 7. Technical Targets for On-Board Charger

On-Board Charger Targets	2025	2030	2035
Power Level	6.6	19.2	19.2
Voltage	600	800	800
Cost, $/kW	30	20	16.67
Specific power, kW/kg	4	12	12.8
Power density, kW/L	4.6	13.7	14.8
Efficiency	98%	98.5%	98.5%

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 7 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 EDTT 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.

Value Proposition

Understanding the potential value proposition a new technology can provide the electrified vehicle will be critical for future targets. Current technical targets are single dimensional and focus on basic performance R&D. Value proposition-based targets will create competitive advantages. This will be accomplished by creating new understanding and opportunities that leverage the highly technical resources/knowledge base present in the U.S. The EDTT will seek out and quantify new functionality and its associated cost and benefits that can be provided through power electronics and electric machines. The target will be to identify and evaluate potential value proposition cases each year. As these cost/benefit studies are completed, those that show promise will be used to set appropriate technical targets. These value proposition targets will be formalized and incorporated into the EDTT Roadmap.

Recyclability

Designing for assembly and disassembly should be a primary consideration. Product design itself is not a result of the work performed on this program, but the development of methods for assembly and disassembly are within scope. For each design approach pursued, a design for assembly and disassembly will be performed.

Current Technical Target Status

The 2022 manufacturing cost of a commercial on-road 100 kW ETDS, consisting of a single electric traction motor and inverter is currently estimated to be $1,140 based on the publicly available data and scaling it for 150kW system.[6] Of this cost, the electric motor accounts for approximately $756 and inverter about $384.

The 2020 EDTT R&D target for the ETDS was $8/kW which was met for a 100kW 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 8 shows comparison of 2025 ETDS technical targets with current on-road technology status. A significant size reduction is required to increase the ETDS power density by 733%, while achieving the necessary cost reduction. The complexity of achieving the power density while reducing cost by 47% when compared to on-road technology is dauting.

Table 8. Comparison of Current Status with 2025 Technical Targets for ETDS

ETDS Targets	On-road Status	2025 R&D Target	2025 versus On-road
Cost, $/kW	7.6	4	-47%
Power density, kW/L	6	50	+733%

Table 9 presents the same comparison as above for power electronics and electric motors.

Table 9. Current Status and 2025 Technical Targets for Power Electronics and Electric Motors

	On-road Status	2025 R&D Target	2025 versus On-road
Power Electronics			
Cost, $/kW	2.6	1.8	-30%*
Power density, kW/L	30	150	+400%
Electric Motor			
Cost, $/kW	5.0	2.2	-56%
Power density, kW/L	9	75	+733%

*On-road cost doesn't represent a SiC-based system, which will have significantly higher cost.

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[6] UBS, "UBS evidence lab electric car teardown: Disruption ahead?" (2017), https://neo.ubs.com/shared/d1ZTxnvF2k/" icct The International Council of Clean Transportation, Working Paper 2019-06

The on-road inverter and electric motor cost assessment is based on information from the International Council on Clean Transportation (ICCT) Working Paper 2019-06. Cost information was presented from the working paper for 2017 along with projected cost in 2025 that was then extrapolated for 2023. Additionally, information presented at the Vehicle Technology Office annual merit reviews from industry projects were used along with other public source information to check reasonableness. It is important to note that current on-road inverter uses silicon insulated-gate bipolar transistors (IGBTs). The introduction of SiC to achieve higher efficiency over the drive cycle and higher power density will significantly increase the cost being reported as On-road.

Gaps and Barriers to Reach 2025 Technical Targets

Cost and size are the key barriers to achieving the EDTT 2025 ETDS technical R&D targets and increased EDV market penetration. The cost needs to be cut and size reduced by an order of magnitude (Table 8), and reliability need to be doubled 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:
  - Improved materials (i.e., copper, e-steel) to cut costs and increase reliability
  - Heavy-Rare-Earth-Free machines in anticipation of rare-earth magnet price spike
  - Higher peak power to meet the variety of vehicles offered
    - Develop motor capability for greatly increased motor RPM operation
  - Multi-physics integration (i.e. electrical, magnetic, thermal, fluids, mechanical , reliability and materials considerations) of power electronics to cut size and enable in-situ technology insertion
  - Design for assembly and disassembly
    - Enable cost-effective recycling of materials
    - Improve manufacturing by improving productivity

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. It will be critical to co-optimize the entire power electronic system using multi-physics principles, as WBG devices simply “dropped in” to existing circuit designs will under-perform and will not be cost-effective. Rather, an integrated ecosystem is necessary wherein active WBG semiconductor switches, power modules, magnetic components, capacitors, circuit topology, and controls are all developed concurrently to optimize both electrical and thermal performance.

Power Electronics

Technical barriers and challenges for power electronics are:

- **WBG device power and voltage levels and availability**. SiC devices are commercially available for automotive use, but they are still prohibitively expensive. Finding the value proposition that justifies the incorporation of SiC is a critical barrier. GaN devices are not ready for use in automotive qualified 800V+ and 150 kW ETDS. Manufacturing processes to improve yield of both SiC and GaN are needed to address cost and device defect rates.
- **WBG multi-physics integration design capability to enable optimal use and reduce overall system cost**. Highly integrated designs will address barriers of electrical performance by reducing inductance and eliminating the number of electrical interfaces. This – along with thermal management - will improve system performance and reduce costs.
- **High-temperature and isolation materials**. Higher orders of integration, derived from the above multi-physics developments, create the need for components/materials to handle the greater demands caused by the closer proximity of functions to one another. To address the power electronics barriers, R&D is needed to close the following technical gaps:
  - Higher power and high-voltage WBG device availability
  - 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.
  - Development of a domestic supply chain.

Electric Motors

Electric motor specific barriers are:

- Magnet cost and rare-earth element price volatility and high cost for heavy-rare-earths
    - Rare-earth mining and magnet processing expanding, but heavy RE cannot expand
- Non-rare-earth electric motor performance
    - Reduction in energy density and increases in NVH and weight expected
- Material property optimization capability (e.g., isolation, conductivity)
- Thermal management techniques for the stator and rotor to maintain efficiency and performance

Most production ETDSs use permanent magnet (PM) motors which contain Nd-Fe-B 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 (dysprosium and terbium) which are needed to prevent demagnetization at high temperatures. Heavy rare-earth prices are volatile (Figure 11), and this is a major concern as today's designs are dependent on them and will impact commercialization. A recent report by the White House has estimated that China controls 55% of the world's rare-earth mining and 85% of the refining process, but essentially 100% of mining and refining for heavy rare earths. This puts the U.S. permanent magnet motor market (and others) in a precarious strategic position.[7]

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[7] The White House, "Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth," June 2021

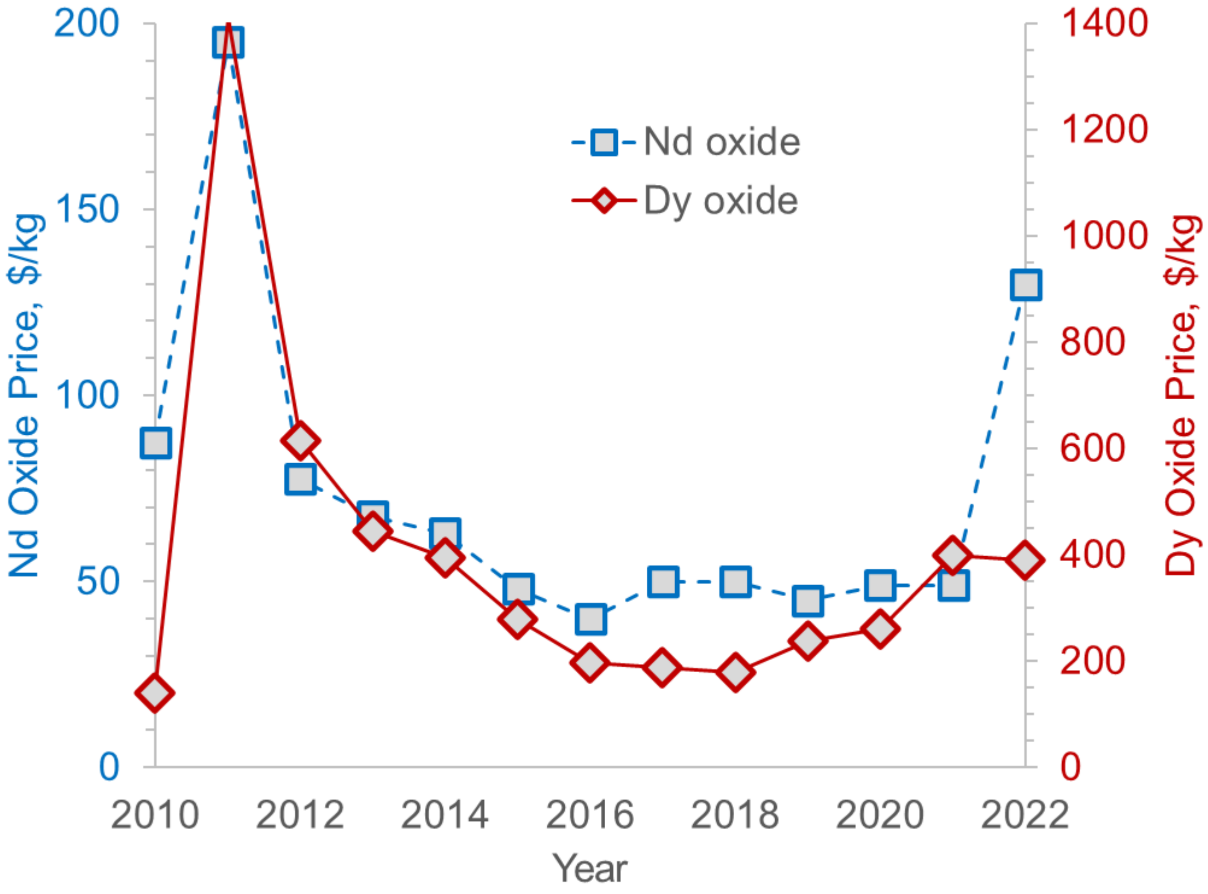


Figure 11. All rare-earth metal prices track oxides very closely and Dy cost is often about 6-8X Nd cost.

Source: Metal Pages courtesy of Critical Materials Institute

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, optimization for miniaturization, cost reduction, and creating an improved value proposition for the consumer. 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 EDTT 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 new materials such as ultra-conducting copper, incorporating advanced thermal management techniques, and use of high-performance computing to accelerate innovation.

R&D pathway for meeting 2025 cost target of $1.8/kW and 150 kW/L:

- Multi Physics Integration
    - Dielectric fluids for thermal management
    - Design tools based on artificial intelligence for optimization
    - Machine-learning and artificial intelligence to calibrate controls based on machine state
- Additional component integration
- Wide-Band-Gap Switches
    - Application with a focus on SiC
        - Characteristics of full automotive operating range
        - Gate Drive circuitry
        - Optimal operating strategies and in-board device fabrication
        - Mitigation of impact of high voltage and high dv/dt switching
        - Signal integrity/high switch count, gate driving power delivery, interleaving for EMI mitigation and redundancy
        - Control strategies to take full advantages of new devices
        - New cooling strategies to support higher integration

- Device
    - GaN design
    - Manufacturing processes and yields
    - Characterization to understand and better apply WBG

The resulting inverter component breakdown cost and percentages showing largest cost contributors are shown in Table 10 and Figure 12.

Table 10. 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**

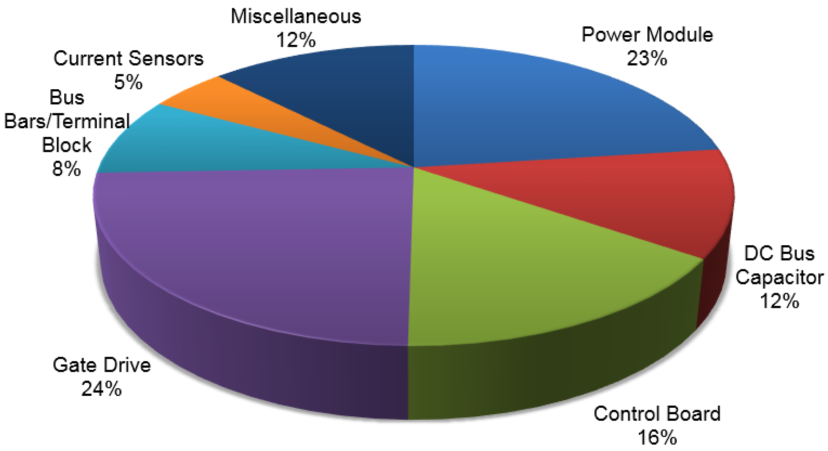


Figure 12. Inverter Cost Breakdown for a Potential Pathway to Meeting 2025 Target

Source: Oak Ridge National Laboratory

Power Electronics R&D Areas

To carry out the power electronics strategy for meeting the 2025 and 2030 targets, specific research is needed in many areas to address the underlying issues. Figure 13 presents the power electronics R&D areas and the following text describes the background and issues to be addressed for each one.

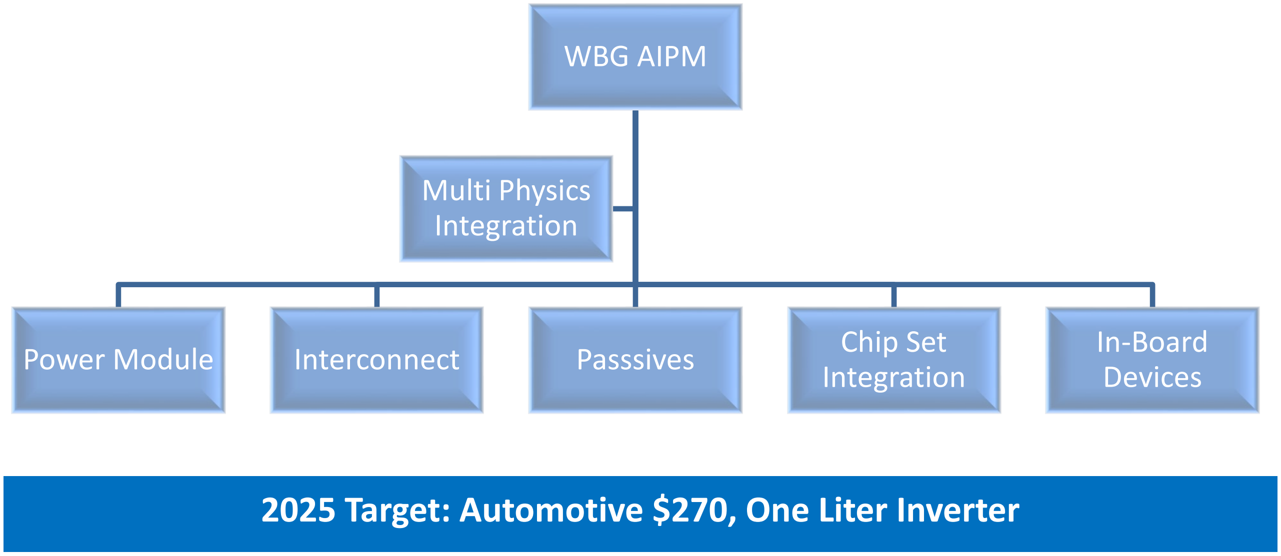


Figure 13. Power Electronics R&D Areas

Multi Physics Integration

Background: Traditional two-dimensional packaging seen in on-road systems is cost effective and allows for larger distances between subcomponents providing for noise and thermal isolation. The downside of long electrical pathways are higher parasitic resistance and inductance, which encumbers the application of WBG devices, 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, manufacturing process capability, 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. The higher-order integration of the power module into the system will demand greater manufacturing process capability be placed with the system integrators versus a few power module producers.

Passives

Passive components typically represent one of the largest costs of 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. Additionally, to meet the needs created by the introduction of WBG devices, capacitor interconnections will be considered.

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. The disadvantages of current capacitor technology are lack of ability for 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 the 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; crosstalk 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, advanced soft magnetic materials, and practical ultra-conductive copper for compact windings. Along with the material improvements, improved fluid-based thermal management strategies can also help achieve the targets. To address these gaps, the main R&D strategy is to reduce cost by using innovative materials processing to improve capabilities and performance of lab-scale materials developments and to apply them in motor design innovations. Materials with improved capabilities and performance include ultra-conducting copper, heavy-rare-earth-free and non-rare-earth magnets, low-cost, high-voltage insulating materials, and improved thermal fillers, epoxies, and varnish materials. These material improvements are applicable to many different electric motor types as shown in Figure 14 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 applying 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.

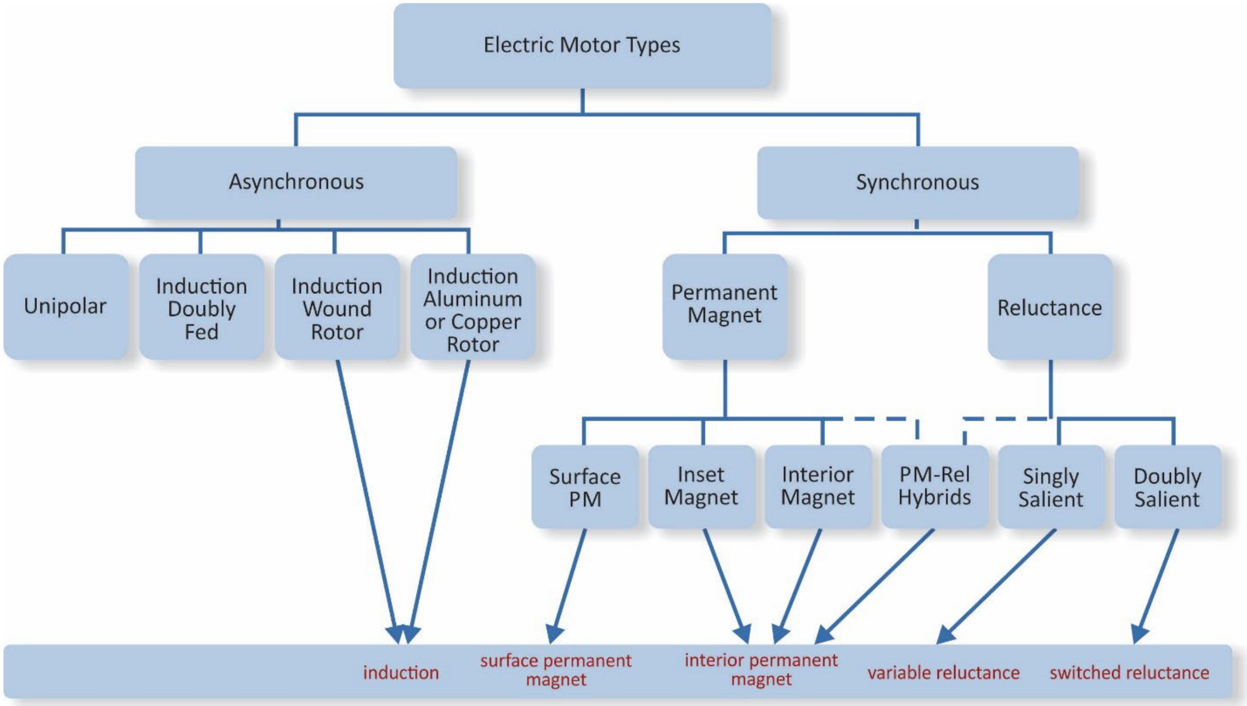


Figure 14. Electric Motor Types

R&D pathway for meeting 2025 cost target of $2.2/kW and 75 kW/L:

- Alternate topologies to traditional interior permanent magnet machines. This may include wound rotors; outer rotor; and high speed
- Materials work: Heavy-Rare-Earth-Free (HRE-free); Multiphysics metamodeling for drive cycle efficiency optimization; Magneto structural topology optimization for optimum material distribution; Amorphous Metal Ribbons (AMR) and Metal Amorphous Nanocomposite (MANC) -soft magnetic materials; Soft Magnetic Composites(SMCs) for motors and power electronics; 6.5% Si steel soft magnetic materials.
- Manufacturing Processes that enable cost-effective ultrafine, oxidation-protected powder production and low temperature sintering for HRE-free permanent magnets; Enable high (6.5%) silicon steel for motor efficiency with cost-effective manufacturing process for high-performance low-cost Fe-Si soft magnetic materials; Develop hot-pressing or spark plasma sintering (SPS) of near net-shape stators, rotors and inductors, using glass ceramic insulation layer application; Cast and additively manufactured high-slot-fill coils with enhanced heat transfer surfaces and die compressed windings.
- Multiphysics Design Tools
- Thermal management for the stator and the rotor.

The resulting electric motor component breakdown cost and percentages showing largest cost contributors are shown in Table 11 and Figure 15.

Table 11. 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**

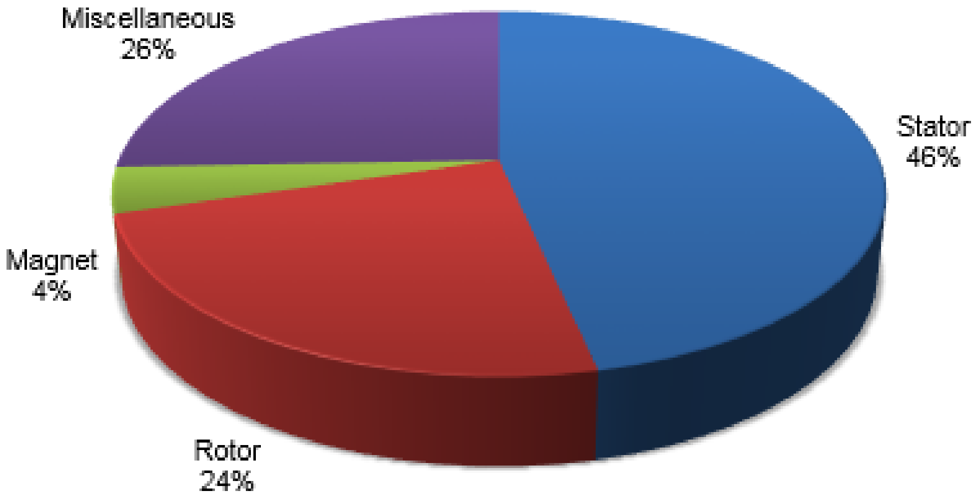


Figure 15. Electric Motor Cost Breakdown for a Potential Pathway to Meeting 2025 Target

Source: Oak Ridge National Laboratory

Electric Motor R&D Areas

To carry out the electric motor strategy for meeting the 2025 and 2030 targets, specific research is needed in many areas to address the underlying issues. Figure 16 presents the electric motor R&D areas and the following text describes the background and issues to be addressed for each one.

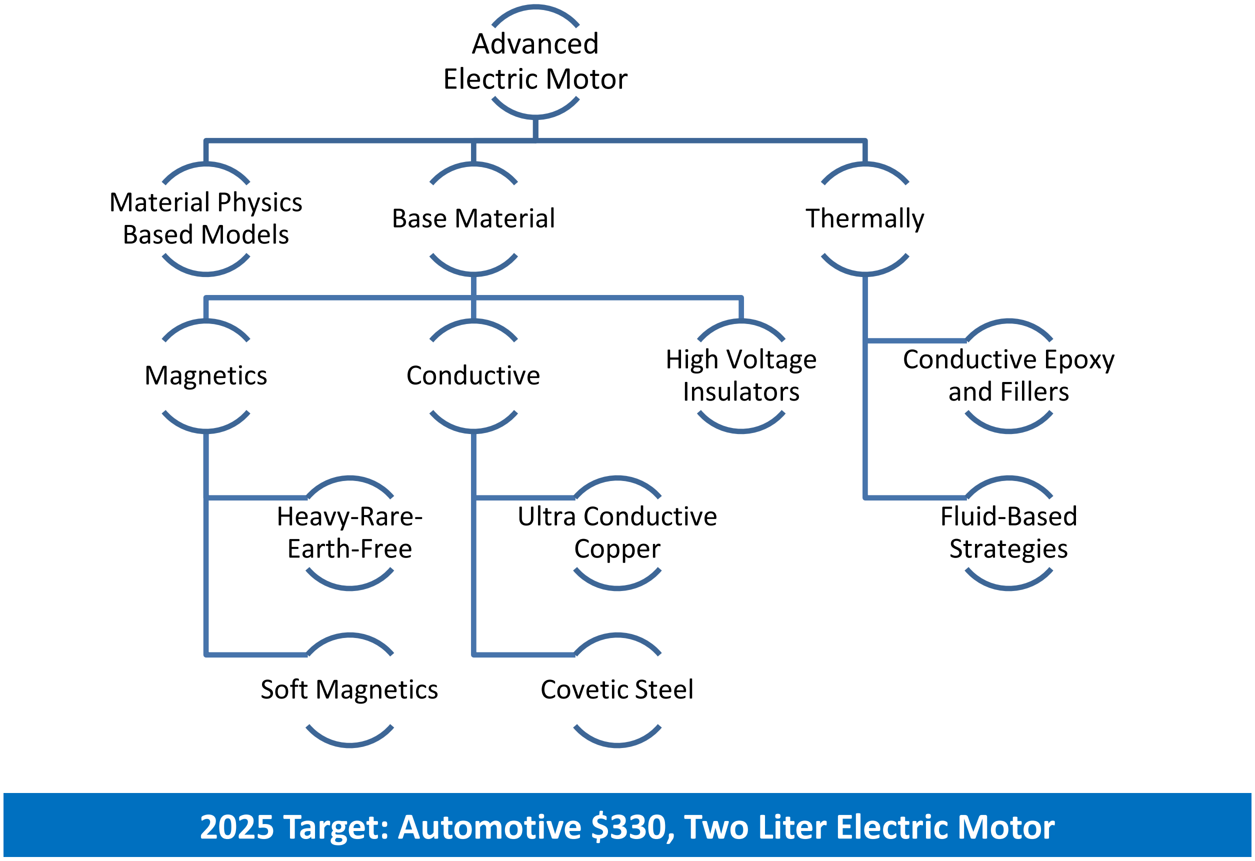


Figure 16. Electric Motor R&D Areas

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 is 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.

Heavy Rare-Earth Free Magnets

Background: Current PM motors use neodymium-iron-boron (Nd-Fe-B) PMs because of their superior magnetic properties. However, current Nd-Fe-B magnets are alloyed with heavy rare earths (HRE) like dysprosium and terbium to tolerate high motor operating temperatures which adds considerable expense with prices that are unstable. Without HRE in the PMs, thermal demagnetization poses limits on motors that require either limiting the duty of the motor or investing heavily in thermal management systems to transport heat from the motor.

Issues to be addressed: Eventually, non-rare-earth magnetic materials are needed that possess magnetic energy density similar to Nd-Fe-B magnets. Besides having similar energy density these new materials must have lower cost and provide even higher temperature capabilities. In the near-term, it is necessary to eliminate HRE use by developing scalable processing methods to produce ultrafine (<2µm) grain size in fully aligned and sintered Nd-Fe-B magnets that permit high temperature drive motor operation limits.

Soft Magnetic Materials

Background: Improved soft magnetic materials are necessary to access sustainable non-heavy rare earth PM motor designs. Additionally, high performance soft magnets can enable innovative motor designs that do not require the use of PMs. Improved soft magnetic materials also make higher power densities and efficiencies in high-speed electric drives accessible through improved inductor performance. These materials require improvements in several areas: higher magnetization, lower losses, higher stacking factors (or approaches that can reduce or eliminate the need for laminations).

Issues to be addressed: Several materials and manufacturing approaches hold great promise for improved soft magnetic materials but must be developed further. These include wide melt spun ribbon and conventional punching of 6.5% Si steel or narrow ribbon "bundle" method for 6.5% Si steel motor segment modules (exterior rotor machine), net-shaped Fe_4N fabricated via spark plasma sintering (SPS), Amorphous Metal Ribbons (AMR) and Metal Amorphous Nanocomposite (MANC), and new approaches to Soft Magnetic Composites (SMCs).

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 that has higher electrical and thermal conductivity is 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 increases 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 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.

Fluid-based Thermal Strategy

Background: Fluid-based active thermal management is necessary to ultimately transfer heat from the motor and drive system. The fluid-based active thermal management influences the effectiveness of materials in the motor and their reliability. Current approaches use water-ethylene glycol-based coolants and/or driveline fluids such as automatic transmission fluid. Challenges depend on the motor type and often include removing heat within the motor through multiple materials or interfaces. Other challenges include more compact integration of the power electronics with the motor and the associated need to compactly integrate the fluid-based thermal management for the power electronics and motor.

Issues to be addressed: Key focus areas for research include: 1) Implementation of fluid-based active cooling closer the heat sources to increase the power capability of the motor, 2) Integration of motor and power electronics thermal management to reduce volume and mass, and 3) utilization of improved fluids such as driveline fluids developed specifically for the needs of electric drive propulsion systems to support improved performance and efficiency.

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

Requirement	Current State-of-Art (WBG)	AIPM (Nominal)	Scalability
Peak power (kW)	**30**	**150**	**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 (Arms)		600	800
Precharge time – 0 to 200 Vdc (seconds)		2	2
Maximum efficiency		> 98	> 98
Torque ripple (%)		NA	
Output current ripple – peak to peak (%)		<= 5	TBD
Input voltage & current ripple (%)		<= 5	TBD
Current loop bandwidth (kHz)		10-20	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 ($1.80/kW) @ 1M/units	**$732**	**$270**	**$540**
Volume (@150kW/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

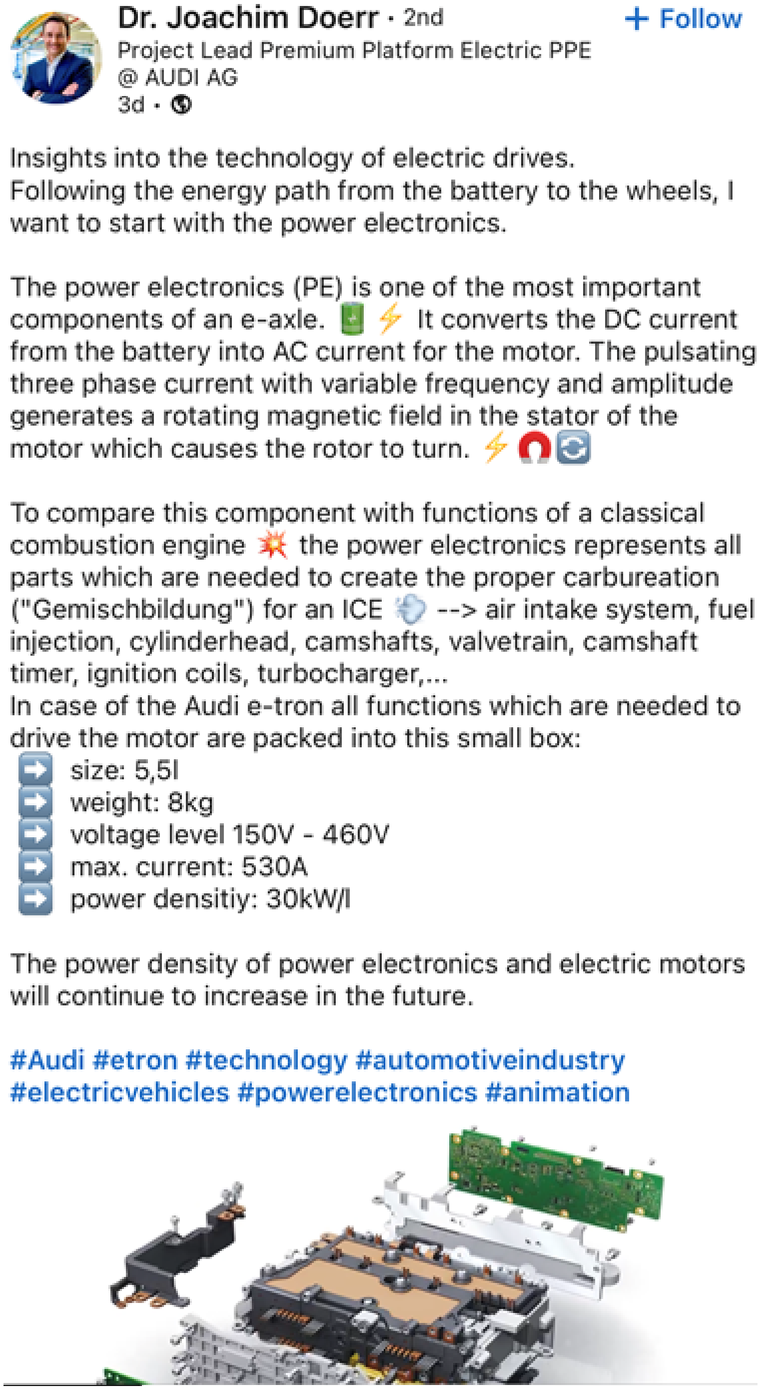
	Current State-of-Art	150 kW	200 kW
Galvanic isolation	Yes (cap > 10pF)	Yes (cap < 10pF)	Yes (cap < 10pF)
High sinking and sourcing current (A)	+/- 20	+/- 30	+/- 30
Active miller clamping/crosstalk suppression	No	Yes	Yes
Under voltage lockout (UVLO) function	Yes	Yes	Yes
Thermal protection function	No	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**	**150**	**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 (Arms)		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 and current ripple (%)		<= 5	TBD
Current loop bandwidth (kHz)		10-20	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 ($2.200/kW) @ 1M/Units	**$448**	**$330**	**$660**
Volume (@50 kW/l)		**2.0 l**	**4.0 l**
Mass (@5kW/kg)		**20 kg**	**40 kg**

Appendix C – Public Inverter and Motor Information



Dr. Joachim Doerr · 2nd
Project Lead Premium Platform Electric PPE
@ AUDI AG
3d ·

Insights into the technology of electric drives.
Following the energy path from the battery to the wheels, I want to start with the power electronics.

The power electronics (PE) is one of the most important components of an e-axle. 🔋 ⚡ It converts the DC current from the battery into AC current for the motor. The pulsating three phase current with variable frequency and amplitude generates a rotating magnetic field in the stator of the motor which causes the rotor to turn. ⚡🧲🔄

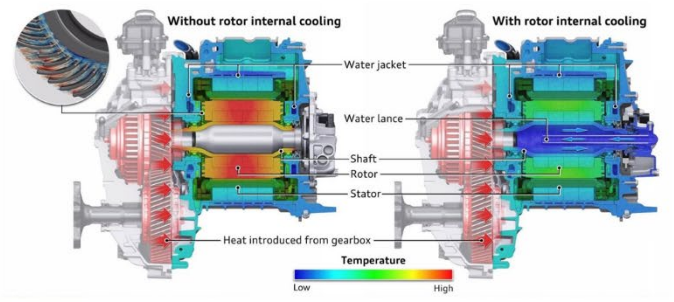
To compare this component with functions of a classical combustion engine 💥 the power electronics represents all parts which are needed to create the proper carbureation ("Gemischbildung") for an ICE 💨 --> air intake system, fuel injection, cylinderhead, camshafts, valvetrain, camshaft timer, ignition coils, turbocharger,...
In case of the Audi e-tron all functions which are needed to drive the motor are packed into this small box:

- ➡️ size: 5,5l
- ➡️ weight: 8kg
- ➡️ voltage level 150V - 460V
- ➡️ max. current: 530A
- ➡️ power densitiy: 30kW/l

The power density of power electronics and electric motors will continue to increase in the future.

#Audi #etron #technology #automotiveindustry #electricvehicles #powerelectronics #animation

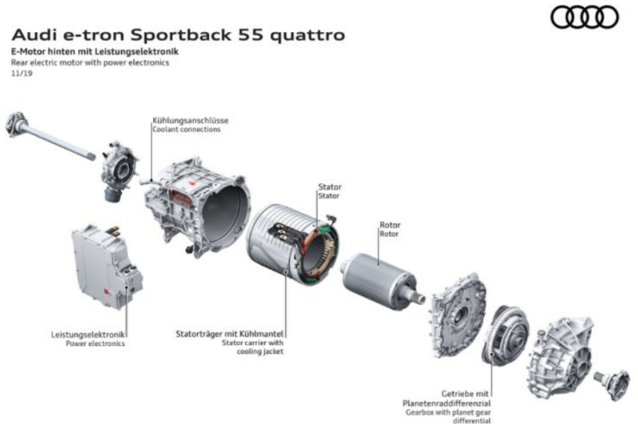
This diagram shows how the rotor internal cooling helps keep the temprature low.

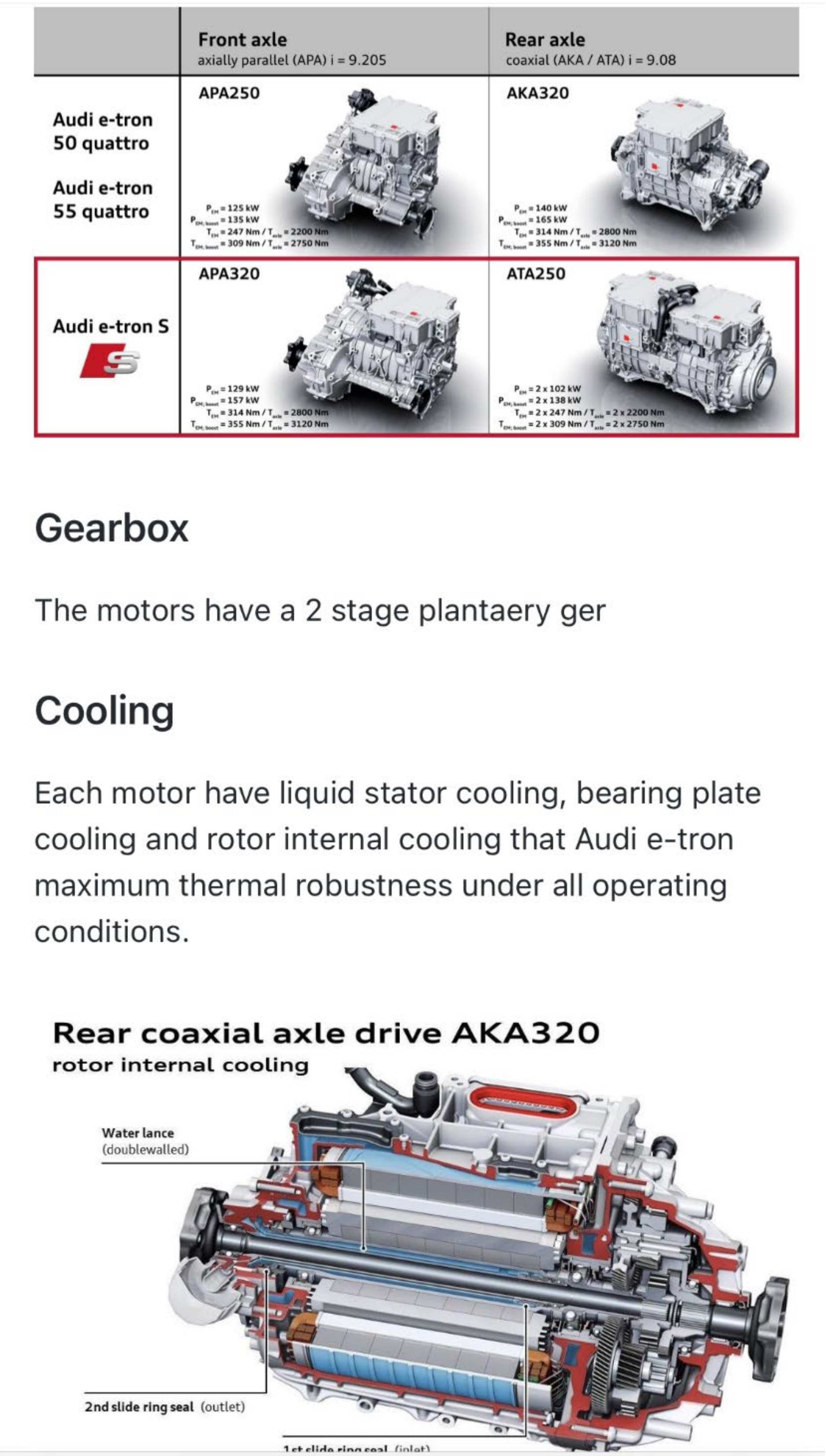


e-tron 50 & e-tron 55

For both e-tron 50 and e-tron 55 Audi uses the AKA320 drive unit for the rear. This is a drive unit with 314nm torque (355nm with boost on e-tron 55) and it has a coaxial configuration on the axels (axels goes through the unit)

With boost





	Front axle axially parallel (APA) i = 9.205	**Rear axle** coaxial (AKA / ATA) i = 9.08
Audi e-tron 50 quattro **Audi e-tron 55 quattro**	**APA250** P_{EM} = 125 kW $P_{EM;boost}$ = 135 kW T_{EM} = 247 Nm / T_{axle} = 2200 Nm $T_{EM;boost}$ = 309 Nm / T_{axle} = 2750 Nm	**AKA320** P_{EM} = 140 kW $P_{EM;boost}$ = 165 kW T_{EM} = 314 Nm / T_{axle} = 2800 Nm $T_{EM;boost}$ = 355 Nm / T_{axle} = 3120 Nm
Audi e-tron S	**APA320** P_{EM} = 129 kW $P_{EM;boost}$ = 157 kW T_{EM} = 314 Nm / T_{axle} = 2800 Nm $T_{EM;boost}$ = 355 Nm / T_{axle} = 3120 Nm	**ATA250** P_{EM} = 2 x 102 kW $P_{EM;boost}$ = 2 x 138 kW T_{EM} = 2 x 247 Nm / T_{axle} = 2 x 2200 Nm $T_{EM;boost}$ = 2 x 309 Nm / T_{axle} = 2 x 2750 Nm

Gearbox

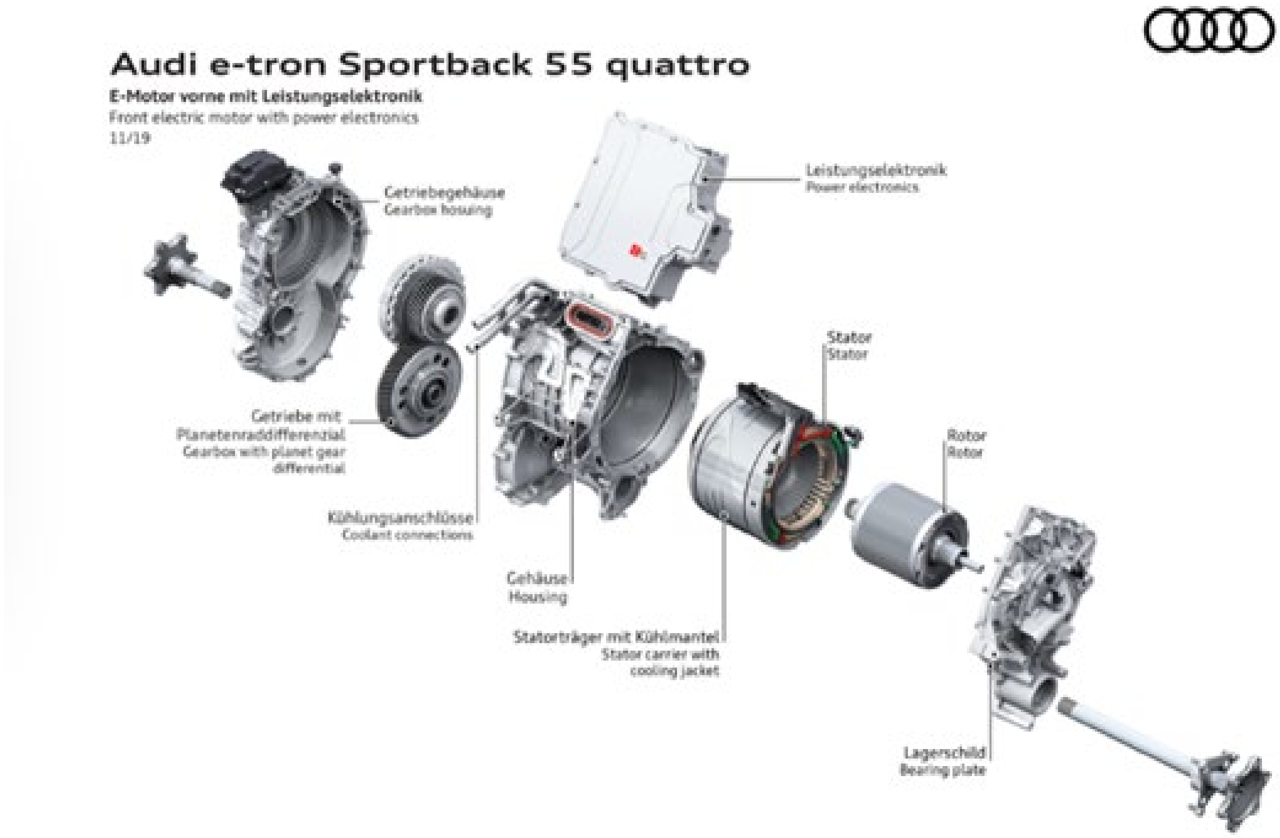
The motors have a 2 stage plantaery ger

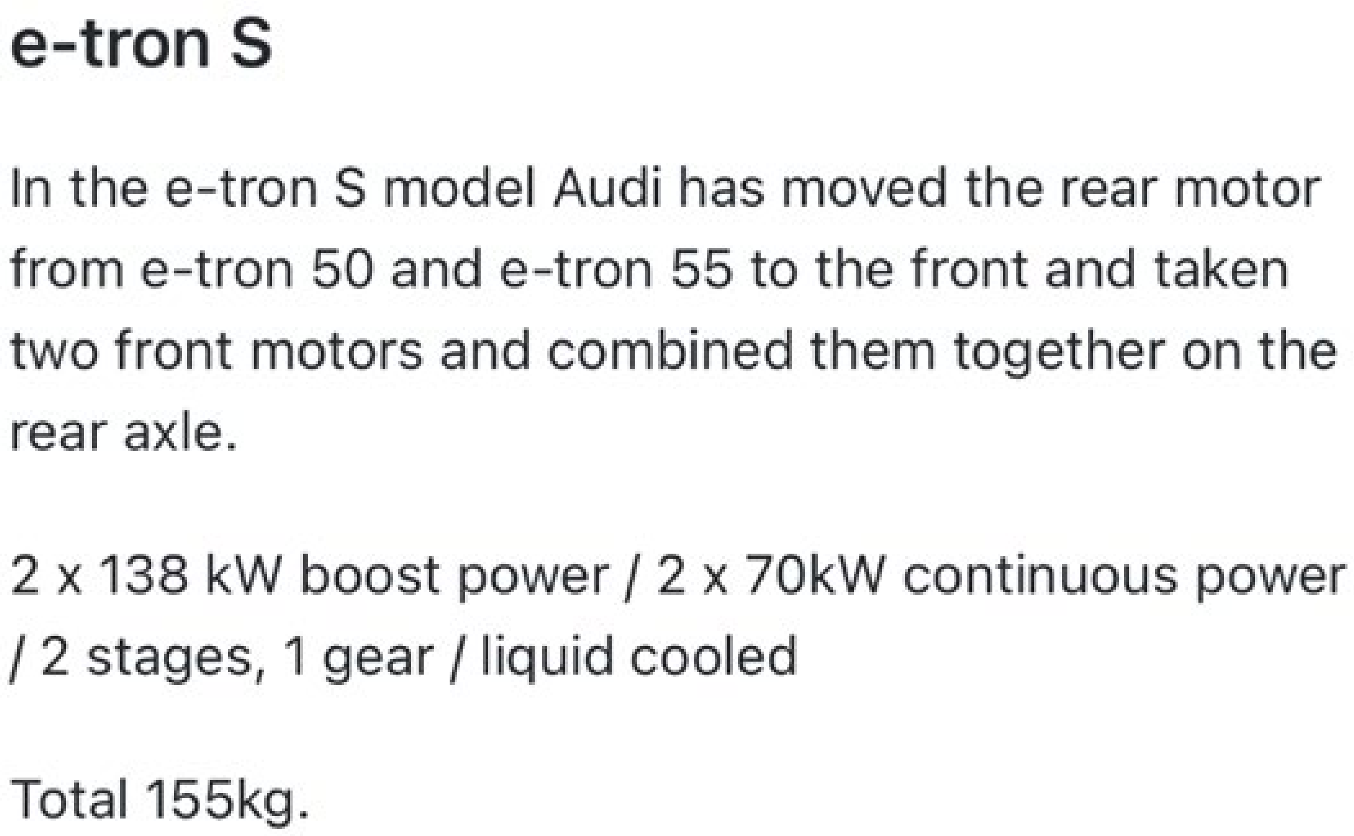
Cooling

Each motor have liquid stator cooling, bearing plate cooling and rotor internal cooling that Audi e-tron maximum thermal robustness under all operating conditions.

Rear coaxial axle drive AKA320

rotor internal cooling


Audi e-tron Sportback 55 quattro
E-Motor vorne mit Leistungselektronik
Front electric motor with power electronics
11/19
Getriebegehäuse
Gearbox housing
Leistungselektronik
Power electronics
Getriebe mit Planetenraddifferenzial
Gearbox with planet gear differential
Kühlungsanschlüsse
Coolant connections
Gehäuse
Housing
Stator
Stator
Rotor
Rotor
Statorträger mit Kühlmantel
Stator carrier with cooling jacket
Lagerschild
Bearing plate

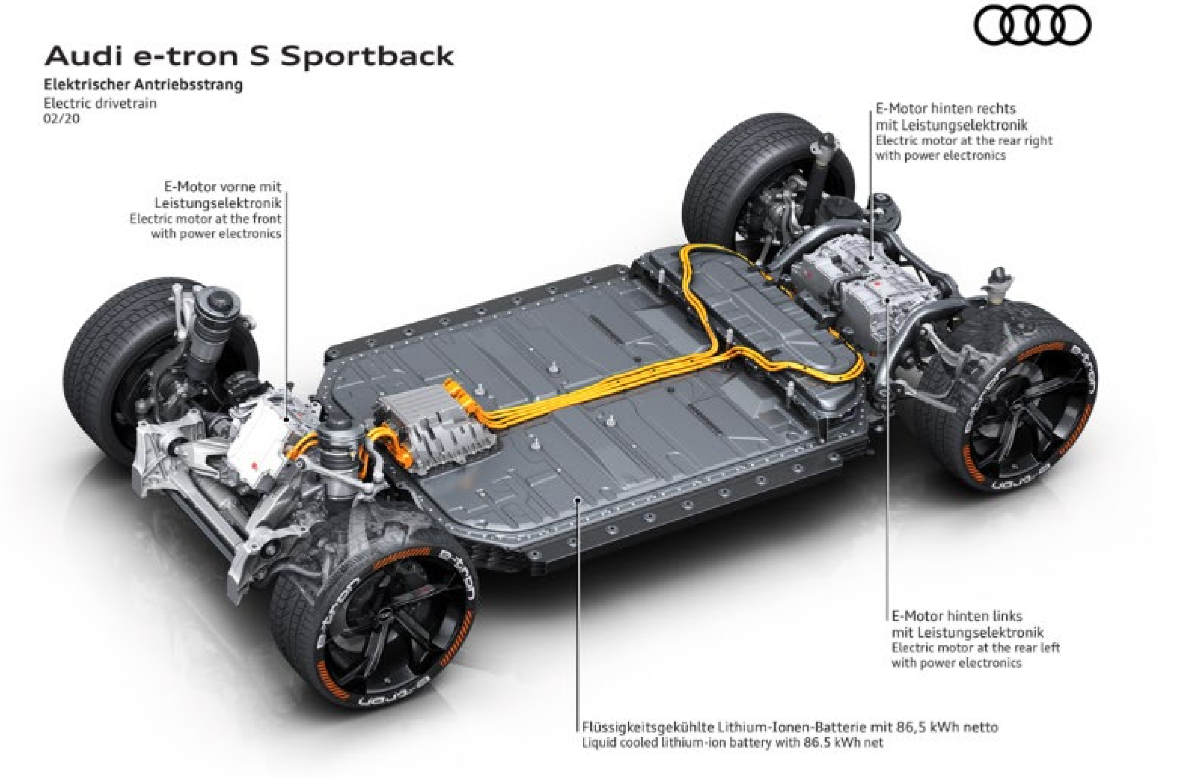


e-tron S

In the e-tron S model Audi has moved the rear motor from e-tron 50 and e-tron 55 to the front and taken two front motors and combined them together on the rear axle.

2 x 138 kW boost power / 2 x 70kW continuous power / 2 stages, 1 gear / liquid cooled

Total 155kg.


Audi e-tron S Sportback
Elektrischer Antriebsstrang
Electric drivetrain
02/20
E-Motor vorne mit Leistungselektronik
Electric motor at the front with power electronics
E-Motor hinten rechts mit Leistungselektronik
Electric motor at the rear right with power electronics
E-Motor hinten links mit Leistungselektronik
Electric motor at the rear left with power electronics
Flüssigkeitsgekühlte Lithium-Ionen-Batterie mit 86,5 kWh netto
Liquid cooled lithium-ion battery with 86.5 kWh net