Quadrennial Technology Review 2015

Chapter 8: Advancing Clean Transportation and Vehicle Systems and Technologies

Technology Assessments

Connected and Automated Vehicles

Fuel Cell Electric Vehicles

Internal Combustion Engines

Lightweight Automotive Materials

Plug-in Electric Vehicles

U.S. DEPARTMENT OF ENERGY

Quadrennial Technology Review 2015

Plug-In Electric Vehicles

Chapter 8: Technology Assessments

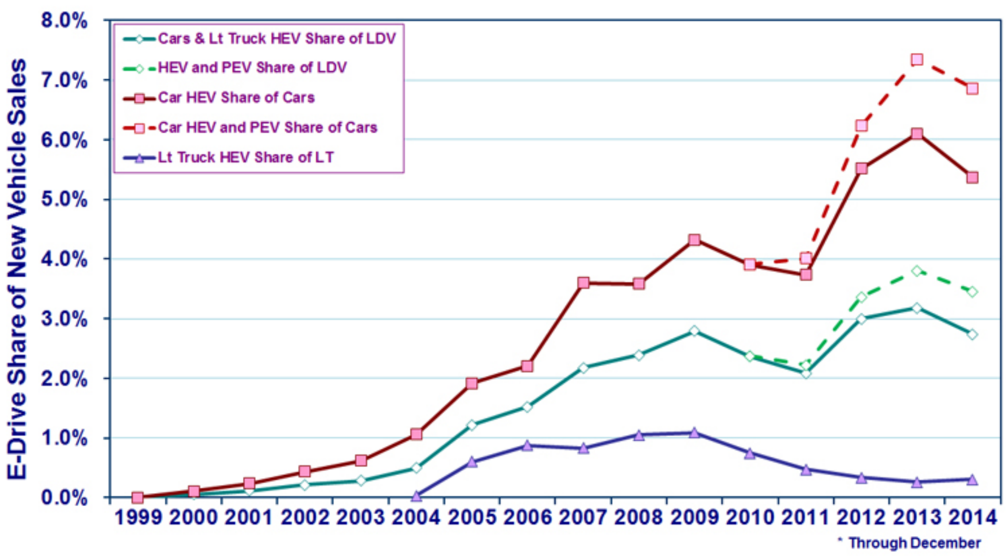
Introduction to the Technology/System

Overview of Plug-in Electric Vehicles (PEVs)

Hybrid Electric Vehicles (HEVs) have reached as high as 6% market share of new cars sold, as shown in Figure 8.E.1. The consumer has a wide range of choices from mild hybrids to full hybrids capable of traveling a significant percentage of miles on electricity. The available portfolio of HEVs has solutions for different usages customers require. Plug-in Electric Vehicles (PEVs) include two basic types: Plug-in Hybrid Electric Vehicles (PHEVs), which can still use fuel as an energy source once the battery is depleted; and Battery Electric Vehicles (BEVs), which only use electricity from the grid stored in their battery systems. PEVs have over 1% of car market share as of 2014 (Figure 8.E.1). Several different types of PEVs with electric ranges from a few miles to well over 250 miles are available to these pioneering customers. PEVs require larger capacity energy storage systems and high power electric drive technologies to enable electric driving with a significant range using electricity.

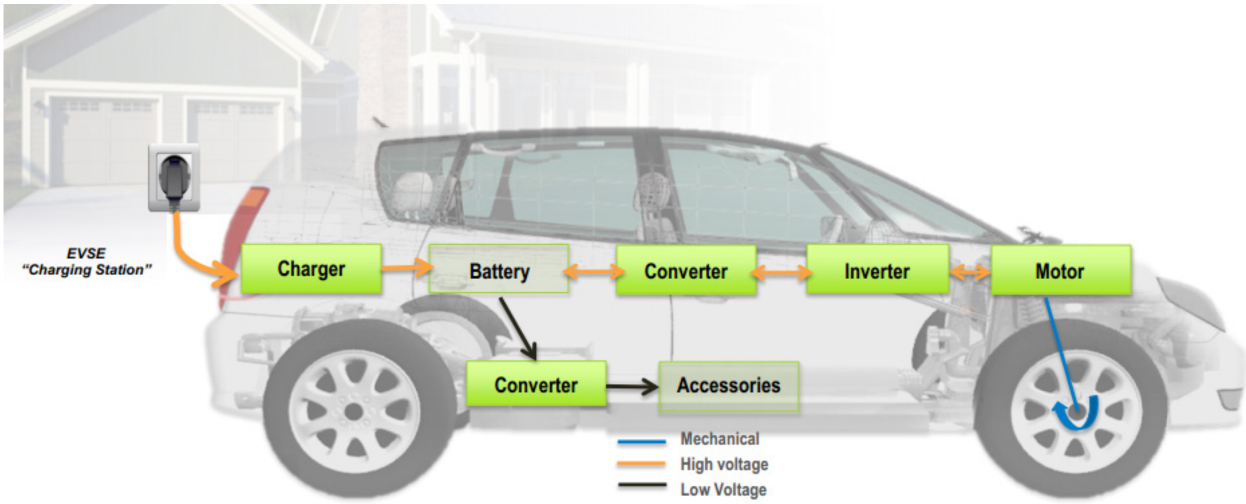
Figure 8.E.1 Historic Market Share of New HEV and PEV Sales

Credit: U.S. Energy Information Administration



Transitioning to a light-duty fleet of HEVs and PEVs could reduce U.S. foreign oil dependence and greenhouse gas emissions, depending on the exact mix of technologies. For a general overview of current electric drive vehicles, see the DOE's Alternative Fuel Data Center's pages on hybrid and plug-in electric vehicles.[1] Figure 8.E.2 highlights the relevant PEV components.

Figure 8.E.2 PEV Schematic showing Battery, Electric Drive Technology components (in green), and Vehicle Systems (Accessories, electric vehicle supply equipment [EVSE] and overall system integration)



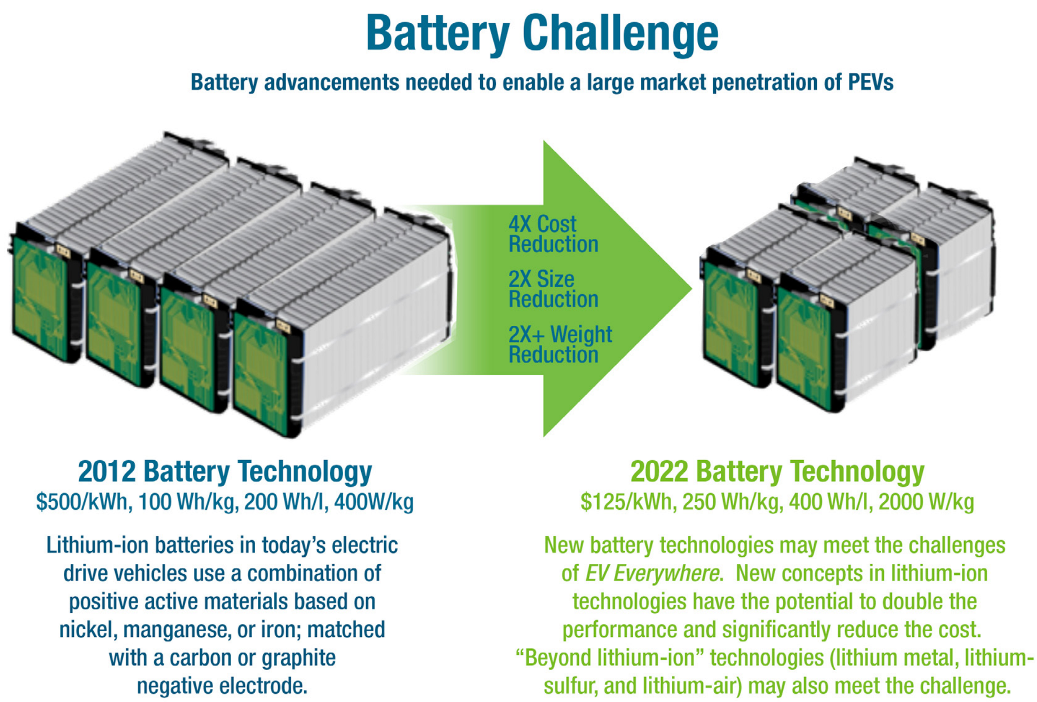
Challenges

A significant number of auto manufacturers have introduced electric drive vehicles but they still comprise only a small portion of the new car market (Figure 8.E.1). The primary reasons are a significant price premium and relatively limited all-electric range. Nevertheless, more and more vehicle models are being electrified and there is a noticeable trend towards higher levels of vehicle electrification (from HEVs to PEVs). At least three automakers are working on all-electric vehicles with a 200 mile range for under $35,000 to be introduced by 2018.

As discussed in detail in Chapter 8, to electrify the nation's light duty transportation sector and enable mass penetration of PEVs in the light duty market, R&D is required in a number of key areas as listed below and illustrated in Figures 8.E.3 and 8.E.4:

Batteries

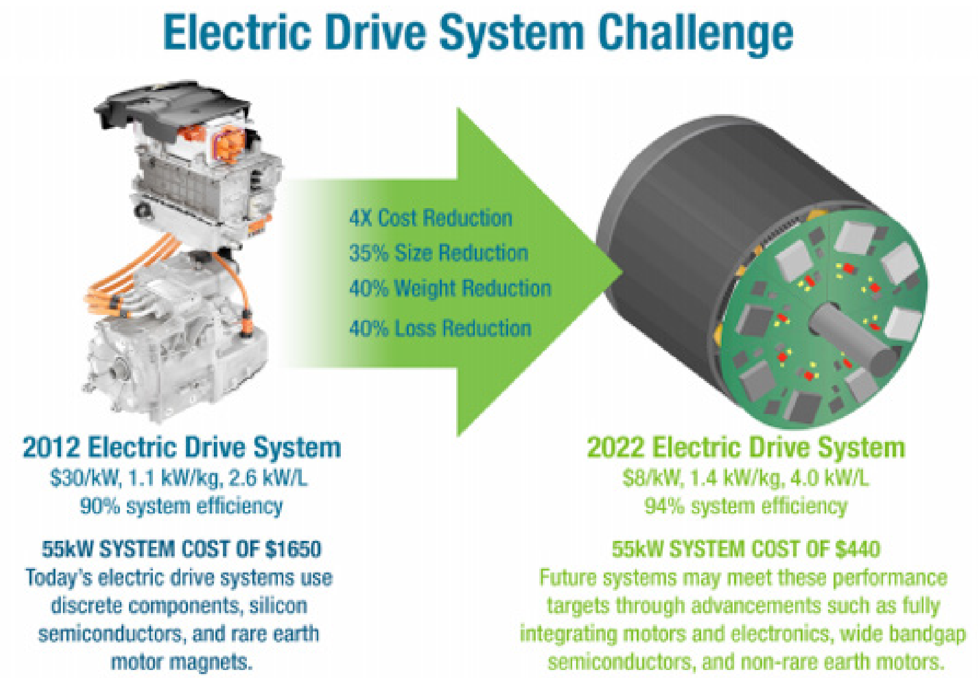
Figure 8.E.3 Battery Performance Advancements Needed for Large Market Penetration of PEVs



- **Cost:** The currently modeled high-volume production cost of high-energy lithium-ion battery packs is approximately $300/kWh, which is about three times too high compared to where it should be for cost-effectiveness (all PEV factors here and below are in comparison to conventional vehicles). These high costs are primarily associated with raw materials, processing, packaging, and manufacturing. To reduce these costs requires improved active materials and packaging/processing methods, and their implementation in cooperation with U.S. suppliers.
- **Performance:** Higher energy densities are needed to meet battery volume and weight targets for PHEV and EV applications. For use in EVs, current batteries for 40-mile PHEV application are approximately two to three times too heavy (and large). Higher energy densities are required. Increased energy density (and correspondingly lower weight) also reduces the necessary amount of material and supporting hardware, further reducing costs. Low temperature performance of batteries also needs to be improved for PEV commercialization success, especially if the battery is the sole power source.
- **Abuse Tolerance, Reliability and Ruggedness:** It is critical that any new technology introduced into a vehicle be abuse tolerant under routine as well as extreme operating conditions. Batteries can be particularly susceptible to abuse. Further, many current types of thermal control technologies for batteries, while adequate at dissipating heat, could be too expensive and would increase system weight/volume.
- **Life:** Batteries undergo a loss in available power and energy due to usage and age. For high-energy batteries in a PEV application, the battery must provide either full vehicle power (for an EV) or high-power HEV pulses (for a PHEV) when near the bottom of its State-of-Charge (SOC) window over the life of the vehicle. Today, while HEV batteries can deliver up to 300,000 shallow discharges, those for PEVs have difficulty reaching the required 5,000 deep discharge cycles.

Electric Drive Technologies

Figure 8.E.4 Electric Drive Performance Advancements Needed for Large Market Penetration of PEVs



- **Cost:** Power electronics, traction motor(s), and controls add several thousand dollars to the vehicle cost, beyond the cost of equipment in a conventional vehicle that they may replace. Without innovation and cost reduction of these components, the cost of electric vehicles will continue to exceed that of conventional vehicles.
- **Size:** Reducing the size of electric drive components will allow more design freedom and simplify vehicle integration, easing electrification of vehicle models and encouraging more widespread electrification of vehicles, which in turn will further reduce component cost by economies of scale.
- **Weight:** Lighter weight Electric Drive Technologies (EDT) components will lower overall vehicle mass and result in more efficient vehicle operation.
- **Efficiency:** Electric drive system efficiency improvements will have a direct impact on either increased all electric range or reduced battery capacity need -- lowering vehicle cost.

Vehicle Systems

The key vehicle systems challenges for PEVs are extending their range and improving the charging of their battery. The battery capacity has a direct and proportional impact on vehicles' range, but scaling the battery also scales cost, mass, and the packaging challenges from a systems perspective. The range is affected by electric drive efficiencies, which for battery electric vehicles (BEVs) range from approximately 65% to 80% on different transient drive cycles. Weight reduction is another key enabler to increase range. Software tools to quantify the range benefits and tradeoffs of these different technologies and approaches are available.[2] Key issues include the following:

- **System optimization and controls** to augment range and reduce energy consumption. PHEV systems can be especially complex as they must seamlessly integrate both an electric drive and an internal combustion engine, and include large electric drive systems, a large battery pack, an internal combustion engine, a hybrid transmission, a charger, and a number of support systems.

- **Minimizing accessory loads** (powertrain support systems, climate control system, driver comfort features). A small PEV may use an average of 4 to 5 kW to drive in the city while an electric heater can draw 4 to 5 kW to warm the cabin in freezing temperatures, which translates to half the electric range. Summer air conditioning poses a similar challenge. Even smaller loads (headlights, fans, etc.) can affect the electric range significantly.
- **PEV charging** and the interaction with the grid. Providing charging convenience and reliability are significant challenges, but essential enablers for widespread adoption of PEVs. Key issues in PEV charging and grid integration include the following:
  - **Infrastructure:** establishing widespread public and workplace charging, especially rapid charging, requires development of a broad network of high power 50 kW charging stations along key transportation corridors.
  - **Codes and standards:** ensuring interoperability between PEVs and the charging infrastructure requires development of physical interfaces, power flow equipment, communications between vehicles and charging stations, test procedures for certifying compliance with codes and standards, and installation/permitting processes.
  - **Grid integration:** integrating PEVs with a modern smart grid to allow the battery capacity of PEVs to provide energy storage to the electric grid requires development of two-way communications protocols with very low latency, and integration of battery capacity with grid dispatch capabilities.

Technology Assessment and Potential

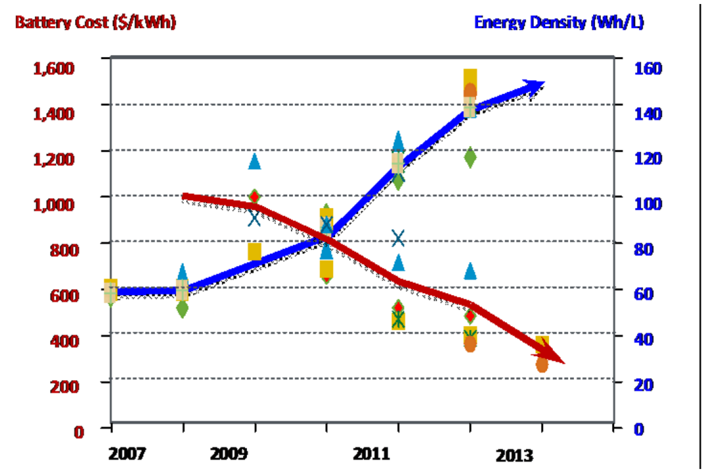
Current commercial PEVs showcase the technology and demonstrate high levels of reliability. The focus of next generation PEV development is on reducing system cost, complexity, size, and weight through system engineering and improved component technologies (i.e., batteries, motors, and power electronics).

Through the EV Project (a project co-funded under the American Recovery and Reinvestment Act (ARRA) that deployed more than 12,000 public charging stations and 8,000 PEVs), PEVs have proven their ability to displace petroleum in the real world, with more than 125 million miles driven. Data from this work found that the PHEVs were driven using electricity for more than 70% of their daily miles, which has direct implications for reducing petroleum use (SAE, 2014).[3]

Batteries

Technology Progress: Over the last decade, battery R&D reduced the cost of lithium-ion batteries by nearly 70% and improved their energy density by 60%. As shown in Figure 8.E.5, the modeled cost of developmental PEV batteries was reduced from $1,000 per kilowatt-hour (kWh) of useable energy in 2008, to about $290 per kilowatt-hour in 2014. Battery cost projections are derived by using he United States Advanced Battery Consortium's (USABC's) battery manufacturing cost model and assuming a production volume of 100,000 batteries per year for battery cells and module designs which meet DOE/USABC requirements for power, energy, and cycle/calendar life – and assuming standard electrolytes and graphite anodes. USABC projects focus on advanced cathodes, processing improvements, cell design, and pack optimization. The developers have obtained significant cost reductions via improved cathodes. The performance has also improved. It is seen in Figure 8.E.5 that the size and weight of PEV battery packs were reduced by over 60% and the battery pack energy density increased from 60 Wh/liter, to more than 150 Wh/liter between 2008 and 2014.

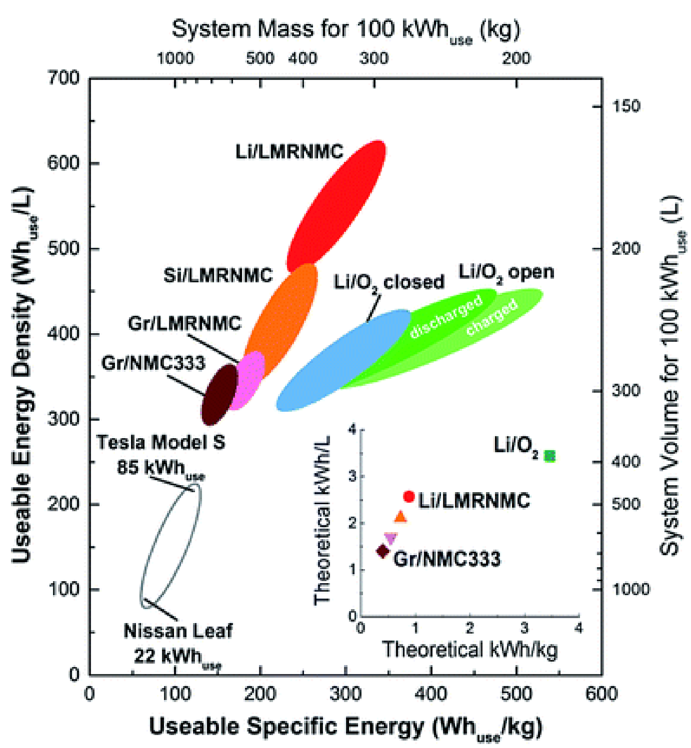
Figure 8.E.5 Modeled Cost and Energy Density of PEV Batteries Developed and Tested[4]



Technology Potential: Current battery technology is very far from its theoretical energy density limit. In the near-term (2015-2020), with advances in lithium-ion technology, there is an opportunity to more than double the battery pack energy density from 120 Wh/kg to 250 Wh/kg through the use of new high-capacity cathode materials, higher voltage electrolytes, separators, and the use of high capacity silicon or tin-based intermetallic alloys to replace graphite anodes (Figure 8.E.6).[5] Despite current promising advances, much more R&D will be needed to achieve the performance and lifetime requirements for deployment of these advanced technologies in PEVs.

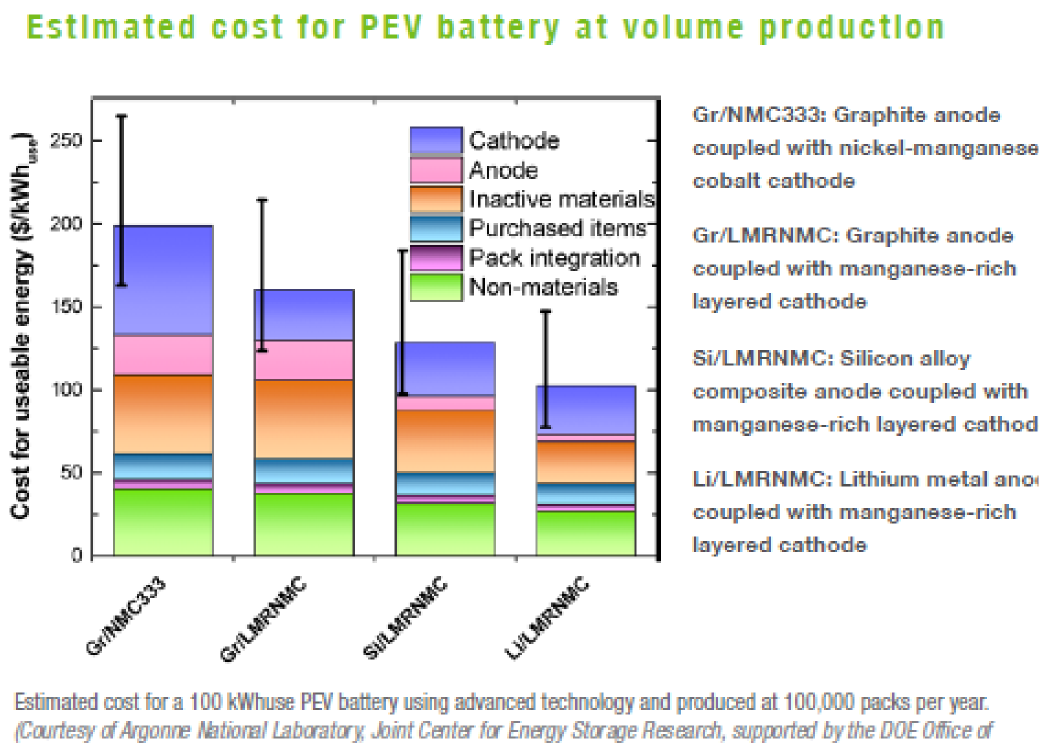
In the longer term (2025-2040), "beyond Li-ion" battery chemistries, such as lithium-sulfur, magnesium-ion, zinc-air, and lithium-air, offer the possibility of energy densities that are significantly greater than current lithium-ion batteries as well as the potential for greatly reducing battery cost.[6, 7] However, major shortcomings in cycle life, power density, energy efficiency, and/or other critical performance parameters currently stand in the way of commercial introduction of state-of-the-art "beyond Li-ion" battery systems. Breakthrough innovation will be required for these new battery technologies to enter the PEV market.

Figure 8.E.6 Calculated systems-level energy density and specific energy for 100 kWh of useable energy and 80 kW of net power at a nominal voltage of 360 V. (inset) Theoretical specific energy and energy density considering both anode and cathode active materials.[8]



The potential of more advanced lithium-ion materials and "beyond lithium-ion" chemistries to reach the goals has been quantified using the Battery Performance and Cost (BatPaC) model developed at Argonne National Laboratory (ANL).[9] This model captures the interplay between design, performance, and cost of advanced battery technology. The results (see Figure 8.E.7) show that the combination of lithium- and manganese-rich high-energy cathode (LMRNMC) and silicon alloy anodes can meet the EV Everywhere cost goals, as can lithium metal battery technology. Batteries with silicon alloy anodes (Si/LMRNMC) and lithium metal batteries (Li/LMRNMC) are estimated to be able to meet the $125/kWh target cost.

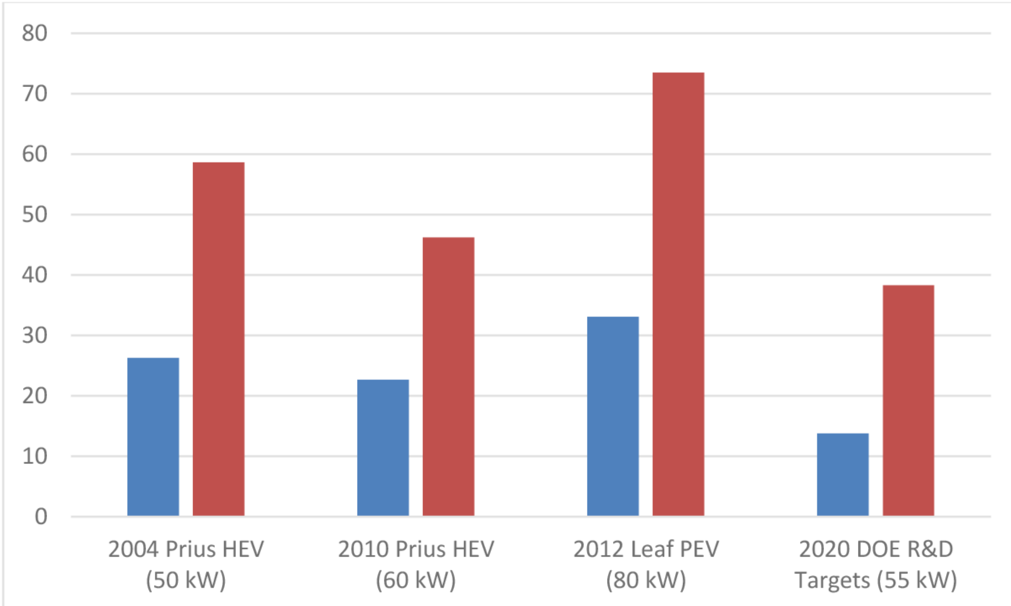
Figure 8.E.7 Estimated Cost for PEV Battery at Volume Production[10]



Electric Drive Technologies

Technology Progress: Over the last decade, significant advances were made in power electronics and electric motor power density and specific power. Figure 8.E.8 shows some of the data from ORNL Benchmarking activities showcasing the generational advancements in these two key target parameters for HEVs (2nd vs. 3rd generation Toyota Prius) as well as the first benchmark for a PEVs (Nissan Leaf). Since PEV solely rely on electric drive, unlike HEVs, the first systems were larger and heavier to ensure adequate performance and reliability. Current electric drive systems are comprised of discrete components with silicon semiconductors for power electronics and rare-earth magnets in electric motors. However, as evidenced by new generations of electric drive systems, there is an increasing trend towards component integration, modular and scalable power electronic devices, and reduced rare-earth magnet motors. All of these advancements are contributing to lighter and more efficient electric drive systems.

Figure 8.E.8 System Volume (Liters, blue bars) and Weight (kg, red bars) of Benchmarked On-Road Electric Drive Technologies Compared to R&D Targets[11]

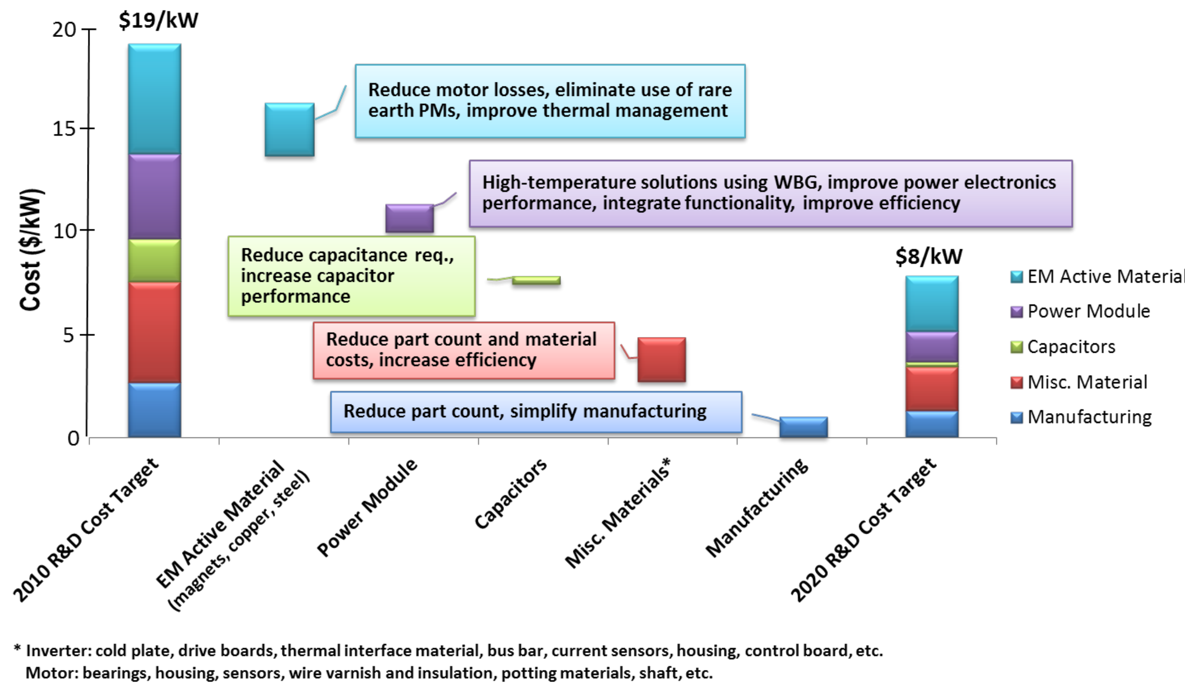


Technology Potential: The focus of ongoing research and development in power electronics and electric motors is reducing the overall system costs and improving performance. The biggest opportunities for cost reduction and performance improvement lie in the following research areas:

- Wide bandgap (WBG) devices for power electronics (see Technology Assessment 6.N) to improve power and voltage handling capabilities, thermal tolerance, reduce the number of devices required in the drive, and others.
- Advanced motor designs to reduce or eliminate rare earth materials[12] and to improve thermal tolerance and reduce costs
- Novel packaging for power electronics and electric motors to reduce weight and volume, and improve thermal management
- Advanced heat exchanger technology to improve thermal management and reliability
- Integration of power electronics functions to reduce weight, volume, and cost
- Wider acceptable system minimum/maximum voltage ratio to permit greater useable energy of batteries, thereby extending vehicle range and reducing battery cost.

Figure 8.E.9 presents an integrated cost reduction pathway for achieving the EDT targets and potential contributions of various electric drive components. Reducing the costs of EDTs to 2022 target costs of $8/kW (includes motor, inverter, converter, and charger) would result in electric drive system cost of $440 for a 55 kW system which would be a dramatic improvement over current production electric drives cost of more than one thousand dollars. Cost reductions are expected to come from both new technology and increased production volume.

Figure 8.E.9 Electric Drive Technology Progress and Potential[13]



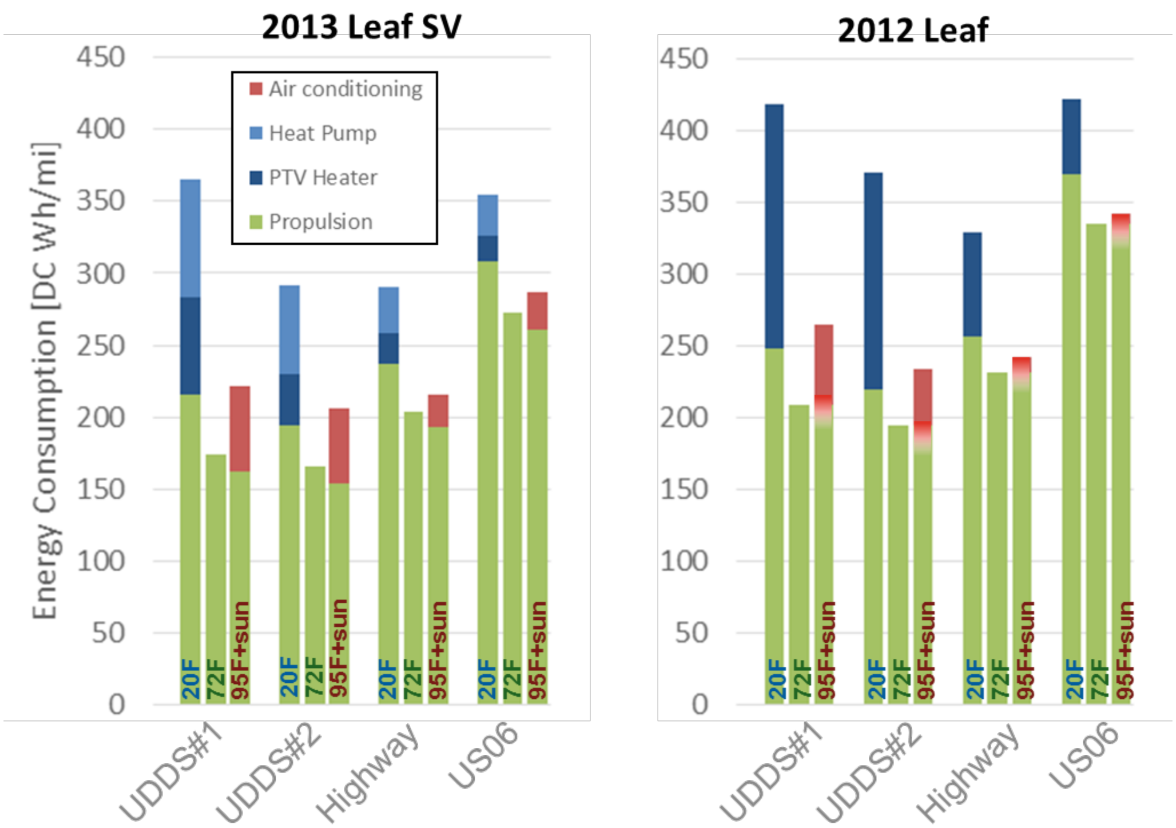
Reducing the size of electric drive components will allow more design freedom and simplify vehicle integration leading to more widespread electrification of vehicle models which in turn will further reduce component cost by economies of scale. Lighter weight of EDT components will result in more efficient vehicle operation. Electric drive system efficiency improvements will have a direct impact on either increased all-electric range or reduced battery capacity need resulting in lower vehicle cost.

These improvements will significantly contribute to meeting the EV Everywhere Grand Challenge goal of making the U.S. the first nation in the world to produce PEVs by 2022 that are as affordable for the average American family as today's conventional gasoline-powered vehicles. In support of this challenge, the electric drive technologies R&D program, developed in partnership with DOE, industry, universities, national laboratories, and others, has targeted reducing cost by half and decreasing volume by one-third for electric drive systems by 2022 through competitively awarded collaborative R&D by national laboratories, universities, and industry and its suppliers.

Vehicle Systems

Technology Progress: The technology evolution of a Nissan Leaf from model year 2012 to 2013 shows the potential for incremental improvement. Figure 8.E.10 shows the energy consumption for different drive cycles and different thermal ambient conditions. The energy consumption is significantly reduced due to aerodynamic improvements, regenerative braking improvements, and energy management. Even BEVs, with their relatively simple powertrain setup, can be optimized through regenerative braking strategies and state of charge controls. The optional heat pump used in the 2013 Leaf assists in warming the cabin which reduces the overall power needed by the climate control system. The range in a 20°F environment on the Environmental Protection Agency's Urban Dynamometer Driving Schedule (UDDS[14]) type city driving increased from under 50 miles to over 60 miles from 2012 to 2013.

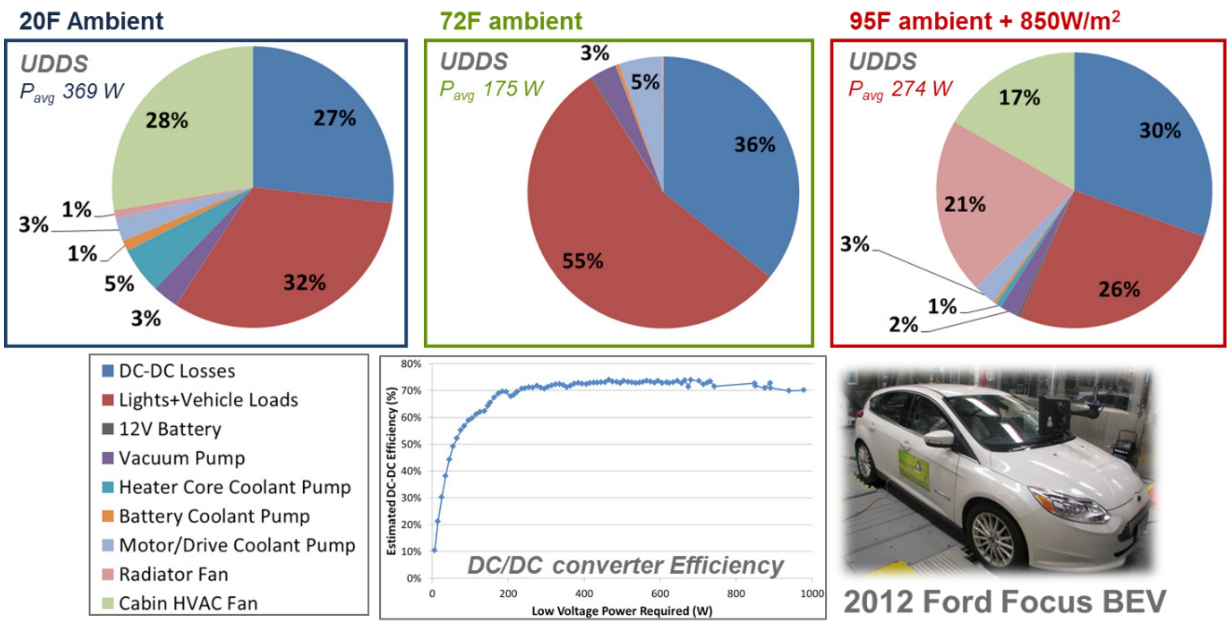
Figure 8.E.10 Energy Consumption Evolution of the Nissan Leaf (model year 2012 to 2013)[15]



Understanding and quantifying today's state of the art in advanced technology vehicles lays the foundation to identify research and technology needs. Fleet testing and laboratory testing of the newest powertrains ranging from prototypes to production vehicles provides data which serve to develop and validate modeling and simulation software, which then enable a fast and methodical exploration of the design space and its potential opportunities.

Rigorous codes and standards are needed to ensure seamless charging experiences for the consumer. Fair test standards are needed to measure technology performances and efficiency benefits. The PEVs high powertrain efficiency results in a high sensitivity of energy consumption and range with respect to driving style and climate conditions, as shown in Figure 8.E.11. The range of a Ford Focus BEV can vary between 112 miles in mild city driving to only 66 miles in aggressive high speed driving at 72°F ambient temperatures. The same vehicle in the same mild city driving may only have a range of 41 miles at 20°F with the climate control set to maximum heat or 54 miles with the air conditioning turned to the coldest setting on a 95°F sunny day (850W/m^2). Research focuses on reducing that variability through accessory load reduction and reducing powertrain losses at low temperatures.

Figure 8.E.11 12V Accessory Load Distribution on the UDDS cycle across Different Ambient Test Conditions[16]



Technology Potential: Major vehicle system innovations that may accelerate PEV adoption in the market are:

- More energy-efficient climate control systems. Potential research areas include:
  - Pre-conditioning of powertrain and cabin (heating or cooling) using grid electricity to reduce battery energy used by accessories
  - Advanced high-efficiency air conditioning systems, potentially including thermal storage, to reduce accessory loads overall as well as peak power demands
  - Better cabin insulation and lower loss/gain windshields and windows, to reduce thermal loads
  - Passenger-focused climate control (e.g., cooled/heated seats, heated steering wheels) to reduce heating/cooling energy use
- Charging system advances:
  - Codes and standards for interoperability to facilitate charging of all PEVs at various service providers
  - Advanced technologies: wireless and DC fast charging to shorten or simplify recharging time
- Integration with the electric grid (i.e., smart charging and vehicle-to-grid services) to minimize charging costs and capture the economic benefits of grid services.

The potential for further system efficiency improvements exists between the thermal management of the powertrain (battery, power electronics, electric motors, etc.) and the cabin temperature. A more integrated approach could yield better overall system efficiencies.

Another system integration area is specific to PHEVs. PHEV technology allows the system to trade-off fuel and electricity to produce heat to warm up the powertrain and cabin at freezing temperatures. Additionally the first engine start can be controlled to reduce cold start emissions. Optimizing the balance between fuel and electric consumption reduction as well as emissions needs further attention.

Potential Impacts

The U.S. Corporate Average Fuel Economy (CAFE) standards for 2025 are challenging regulations for vehicle manufacturers to meet. PEVs could play an enabling role in achieving these targets. Even with a modest market share, PEVs can contribute significantly through their high energy efficiency compared to conventional vehicles. Offering customers PEV technologies with little compromise on cost or range will increase their adoption rate and reduce the nation's petroleum consumption, and therefore increase national energy security. Unlocking further potential benefits of PEVs such as grid integration would not only accelerate the technology's acceptance but also provide benefits outside of the transportation sector.

A transition to electrification will benefit not only the national economy and energy security but also individual consumers—today's PEVs can "refuel" for the equivalent of about $1/gallon, and next-generation vehicles will bring even bigger savings.

Argonne National Laboratory estimates that PEVs could account for 58% of new light vehicle sales by 2030 if current cost and performance targets are met.[17] Corresponding advances in battery and electric drive technologies could reduce national petroleum consumption by 1.48 quads/yr (0.7 million barrels per day) in 2030.

As shown in Figures 8.E.12 and 8.E.13, using technology available by the mid-2030s, PEVs could reduce greenhouse gas (GHG) emissions by roughly 50% and reduce petroleum consumption nearly completely compared to today's gasoline internal combustion engine vehicles (ICEVs). Reductions in GHGs of more than 80% can be reached using electricity from renewable sources. Specifically, BEVs charged with electricity generated from renewable sources (i.e., solar, wind, hydro) can produce as few as 10 grams of CO_2 per mile compared to 430 today and 220 by 2035 for conventional ICEVs.

Figure 8.E.12 Well-to-wheels GHGs Emissions from Advanced Light-duty Vehicle/fuel Pathways, Year 2035[18]

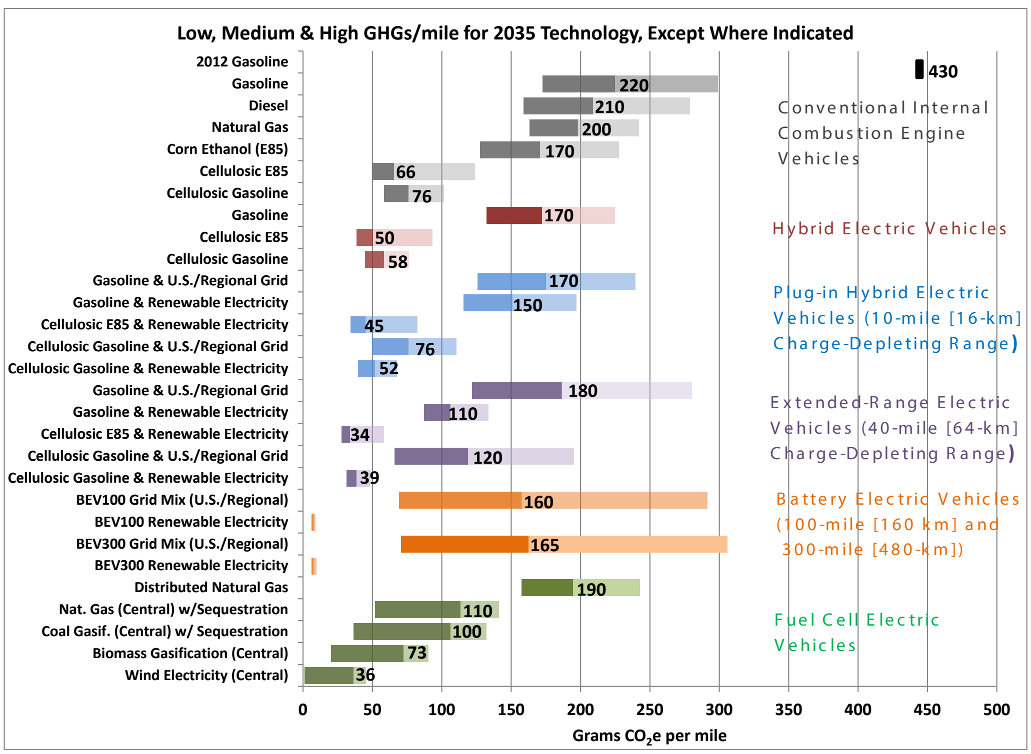
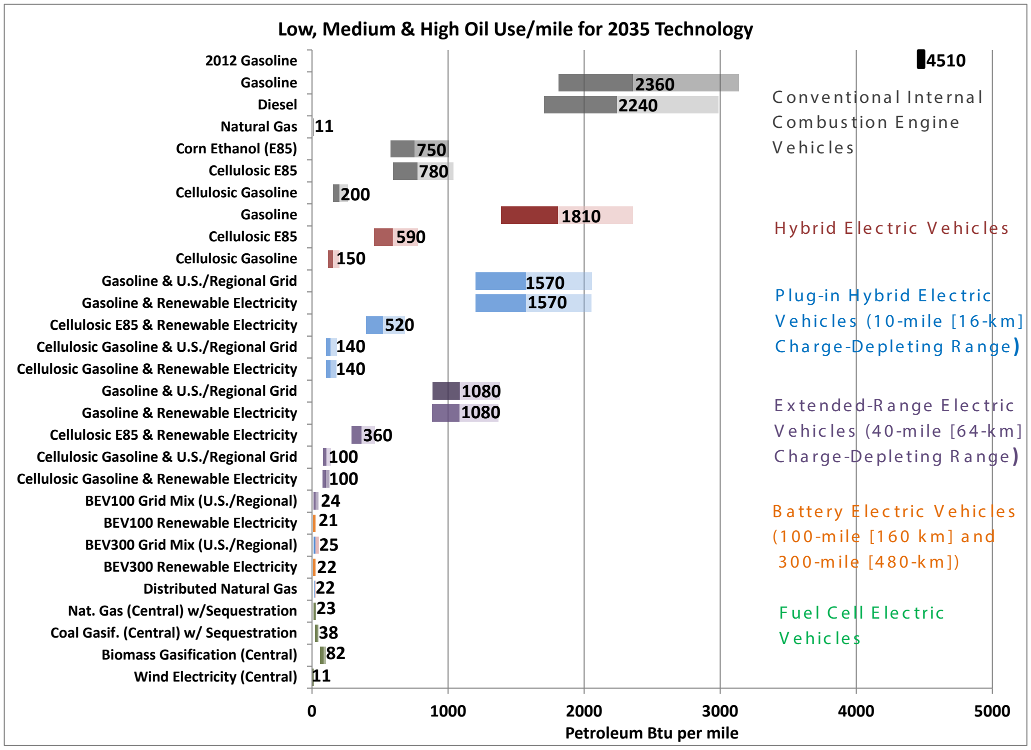


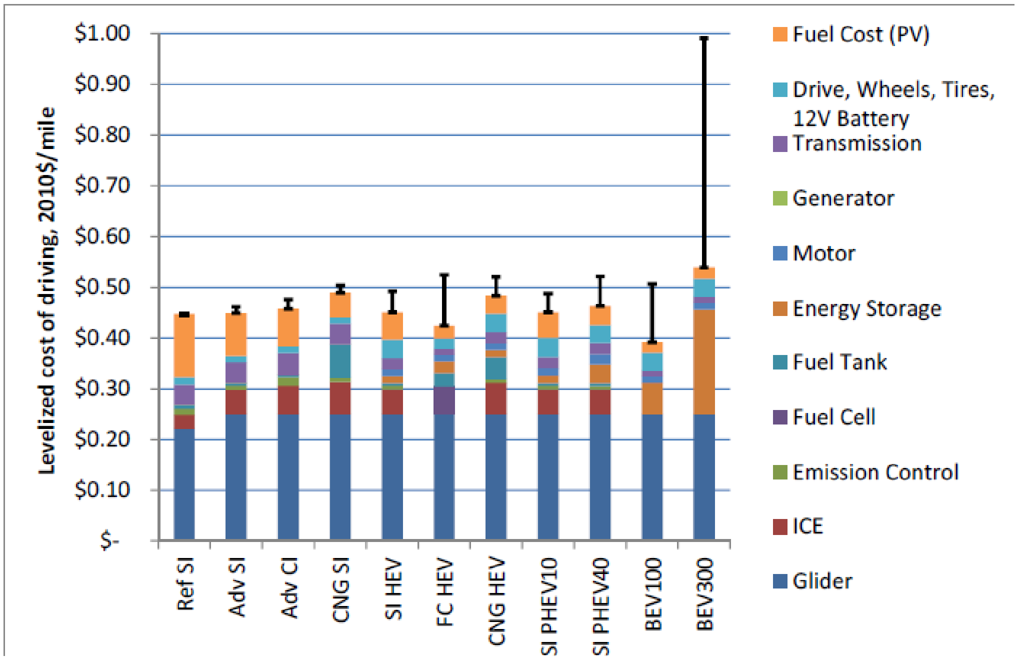
Figure 8.E.13 Life-cycle Oil Consumption from Advanced Light-duty Vehicle/fuel Pathways, Year 2035[19]



PEVs are expected to match the cost of internal combustion engine vehicles in the future as the PEV technology matures and higher production volumes are reached. Figure 8.E.14 shows the projected cost of driving for eleven different powertrains in 2025, assuming five years of ownership and a discount rate of 7%.[20] By 2025, the total cost of ownership approaches that of conventional ICEVs as costs of the advanced powertrains benefit from learning and economies of scale. This finding that PEVs become cost competitive with ICEVs is also demonstrated in a 2013 National Research Council Report.[21]

Figure 8.E.14 Levelized cost of driving in 2025 over five years of ownership assuming a 7% discount rate. Numbers after PHEV and BEV on the horizontal axis represent vehicles' nominal all-electric range. Error bars indicate the projected impact of DOE research programs.[22] Given total 2025 projected light duty vehicle mileage of 3,090 billion miles,[23] a 1 cent/mile savings provides a direct user benefit of about $30 billion in 2025, and further benefits from not importing foreign oil.

Credit: Argonne National Laboratory



Program Considerations to Support R&D

Public and Private R&D Activities

By harnessing the collective knowledge and experience of government, industry, academia, and civil society, PEV RD&D can be accelerated and potentially achieve widespread market adoption. Industry's perspectives on market-driven needs; academia's perspectives on longer-term and more fundamental research; national laboratories perspectives on leading edge and multi-disciplinary research; and civil society's perspectives on public interests all provide critical contributions in establishing high-level strategic priorities and goals in RD&D efforts. These considerations have resulted in public-private collaborations, such as the U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability) Partnership and the United States Advanced Battery Consortium (USABC). Much research is conducted through competitive solicitations to advance new and improved PEV technologies to increase vehicle fuel efficiency in the midterm and facilitate the transition to plug-in hybrid and all electric vehicles.

U.S. DRIVE focuses on pre-competitive, high-risk research needed to reduce the dependence of the nation's personal transportation system on imported oil and to minimize harmful vehicle emissions. A major goal of the partnership is to accelerate the development of pre-competitive and innovative technologies to enable a full range of affordable and clean advanced light-duty vehicles, as well as related energy infrastructure. Partners include DOE, the U.S. Council for Automotive Research (whose members are Ford Motor Company, General Motors Corporation, and Fiat Chrysler Automobiles), Tesla Motors Company, five major energy companies (BP, Chevron, Phillips66, ExxonMobil, and Shell), the Electric Power Research Institute, and two utilities (DTE Energy and Southern California Edison).[24]

The United States Advanced Battery Consortium (USABC) was established in 1991 to support the development of a domestic advanced battery industry whose products can meet the performance requirements of electric drive vehicles. USABC is an umbrella organization for pre-competitive automotive battery research and development among Ford Motor Company, General Motors Company, and Fiat Chrysler Automobiles. Under a cost-shared cooperative agreement with DOE, the USABC supports the development of energy storage systems for the entire range of vehicle electrification platforms, from 12V start-stop, through hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs), to full battery powered electric vehicles (EVs).[25]

Public Roles

Today, our transportation system is heavily dependent on internal combustion engines and oil. In fact, about 90% of our transportation fuel is derived from petroleum and much of this is imported. The need to move away from oil is driven by energy security and vulnerability, cost of foreign oil, cost to consumers, air pollution, greenhouse gas emissions, and the need to develop new vehicle technologies that do not rely on oil. Options include biomass (Technology Assessments 7A and 7B), Hydrogen (Technology Assessments 7D and 8B), and Electric Vehicles. The biomass resource is likely insufficient to meet all transportation requirements; therefore, hydrogen and electricity are the two primary contenders. Electricity is already widespread, so building a recharging infrastructure, though challenging, is not as difficult as for hydrogen. There is a chicken-and-egg challenge of creating a new vehicle technology and widespread charging infrastructure -- the private sector has limited ability to do this given the sheer scale of the challenge, and has little incentive to do this on its own. This then motivates a public role to realize these important potential public benefits. PEVs can decouple personal mobility from oil, cut pollution and help build a 21st Century American automotive industry that will lead the world.

Reducing the cost of electric drive vehicles is essential for increasing consumer adoption. Therefore DOE launched the *EV Everywhere Grand Challenge* in 2012, setting key technical targets necessary for enabling PEVs to be as convenient and affordable as today's gasoline vehicles by 2022. The status and challenges of widespread market penetration of PEV were presented in the *EV Everywhere Initial Framing Document*.[26] Technology development goals and a path forward were set forth in the *EV Everywhere Blueprint*.[27] Both of these were developed through extensive engagement with industry, universities, national labs, and others.

DOE organizations involved in the EV Everywhere Grand Challenge and their roles in these issues include:

- EERE Vehicle Technologies Office (VTO) funds competitive, cost-shared applied R&D. For PEVs, this includes R&D on advanced battery, electric drive, and other enabling technologies shown in Figure 8.E.2.[28]
- Office of Science funds competitive basic science research to provide the foundations for new energy technologies. For EV Everywhere, the Office of Science supports the DOE Energy Storage Hub, the Joint Center for Energy Storage Research, and others (see also Chapter 9, Supplemental Information).[29]
- The Advanced Research Projects Agency - Energy (ARPA-E) funds energy technology projects that translate scientific discoveries and cutting-edge inventions into technological innovations.[30] For EV Everywhere-related technologies, ARPA-E funds competitive research on advanced batteries, super capacitors, chargers, motor-related technologies, and more.[31]

DOE is also addressing the expansion of electric vehicle charging infrastructure through the Workplace Charging Challenge.[32] This partnership aims to increase the number of U.S. employers offering PEV charging to their employees by a factor of ten by 2018. Over 100 Workplace Charging Challenge partners have already joined this challenge, and receive assistance from DOE to help them establish and expand workplace charging.

Batteries

Energy storage R&D efforts range from focused fundamental materials research to battery cell and pack development and testing. The R&D activities involve both short-term directed research by commercial developers and national laboratories and exploratory materials research generally spearheaded by the national laboratories and universities. Figure 8.E.15 illustrates one of the general approaches being used to develop higher energy battery materials, improve battery power, durability, and abuse tolerance, and to significantly reduce cost. In addition to battery materials and design improvements, the US DRIVE Partnership is developing less expensive manufacturing techniques, advanced thermal management technologies, novel packaging, and computer aided engineering battery design tools.

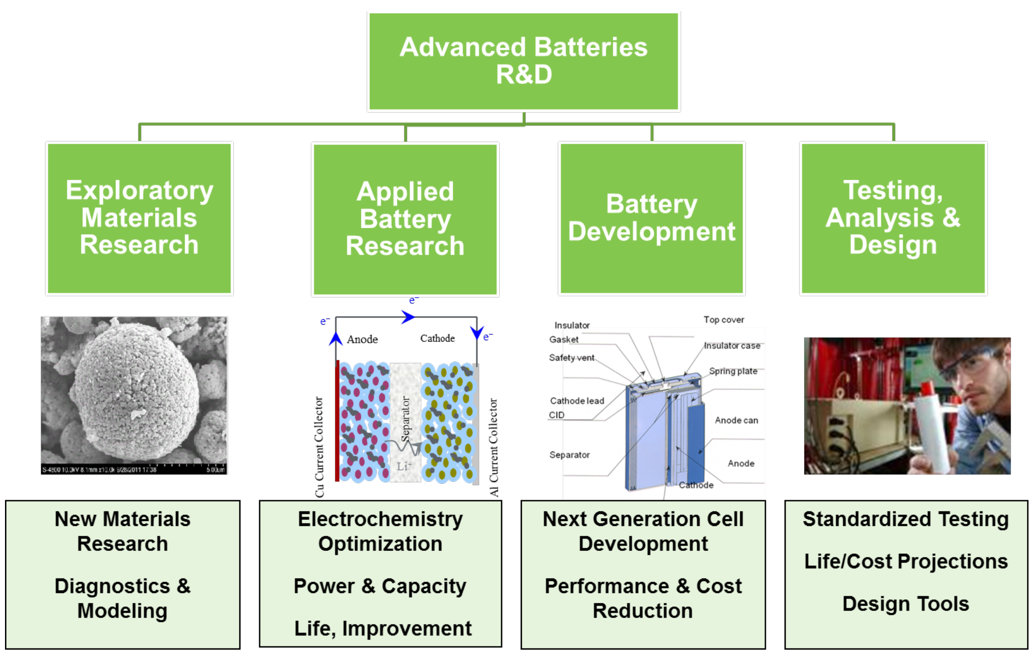
The Battery Technology R&D activity supports focused fundamental research, applied research, and technology development for advanced energy storage technologies (batteries and ultra-capacitors). Battery Technology R&D is focused on achieving the following specific long-term goals:

- Continue to reduce the cost of PEV battery technology, from $1,000/kWh in 2008, to $300/kWh in 2014, to $125/kWh by 2022
- Increase EV battery performance to achieve targets by 2022:
  - Reduce battery size (increase energy density from 150 Wh/L in 2014 to 400 Wh/L)
  - Reduce battery weight (increase specific energy from 125 Wh/kg in 2014 to 250 Wh/kg)
  - Increase battery power (increase specific power from 1,000 W/kg in 2014 to 2,000 W/kg)

Technical details of the R&D strategy are provided in the Electrochemical Energy Storage R&D Roadmap.[33]

Figure 8.E.15 Battery R&D Approach and Process

Credit: Argonne National Laboratory



Electric Drive Technologies (EDT)

The portfolio of electric drive technologies activities spans fundamental research and applied technology development with collaborations among national laboratories, universities, and industry and its suppliers, and technical support for technology maturation and deployment through competitively selected industry/supplier team awards with cost share. The majority of these projects have industry engagement.

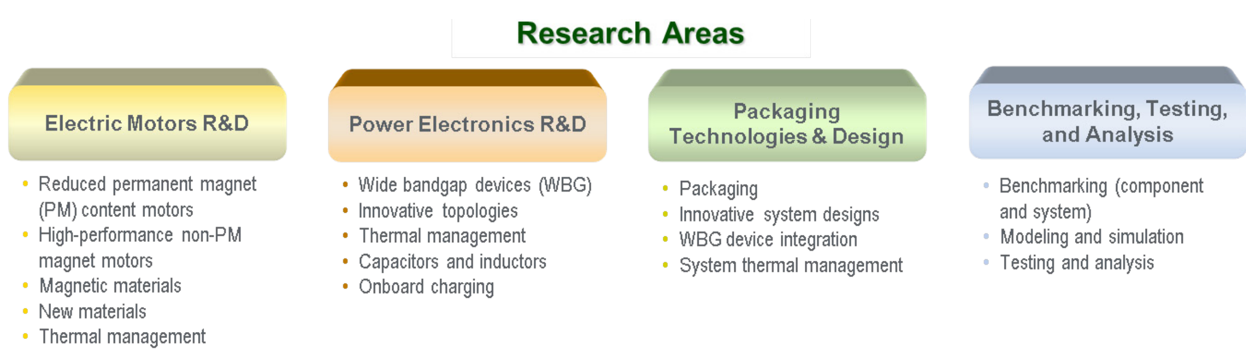
The EDT R&D activity focuses on achieving the following goals:

- Develop technologies to reduce the costs of demonstrated electric drive systems from $30/kW peak in 2012, to the 2015 target costs of $12/kW peak, and then to $8/kW peak by 2022 at 100,000 units annual production. Additionally, the electric drive system shall have an operational lifetime of 15 years and can deliver at least 55 kW of power for 18 seconds and 30 kW of continuous power.
- Develop innovative modular and scalable designs to accelerate the manufacturing capability and mass production adoption of energy-efficient and cost-effective electric drive technologies into electric drive vehicles—hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and all electric vehicles (EVs)

A principal objective of the R&D activity is to reduce component and subsystem cost so that a customer can recover the additional cost for an electric drive vehicle in three years through fuel savings. A detailed technology development roadmap, developed by DOE and industry partners, has been published.[34]

Figure 8.E.16 shows the EDT research areas. Since packaging technologies and design and benchmarking, testing, and analysis are supporting activities to electric motors and power electronics R&D they are included in the more detailed description of these two research areas in the following paragraph.

Figure 8.E.16 DOE EDT Research Areas[35]



Power Electronics

EDT research activity in power electronics primarily focuses on improving inverters as they are the key component and have the biggest impact on power electronic targets. Researchers are working to reduce inverter volume by a third, reduce part count by integrating functionality, and reduce cost. Today's vehicle power electronics utilize silicon-based semiconductors. However, wide band gap (WBG) semiconductors are more efficient, can reduce part count, can withstand higher temperatures than silicon components, and the reduction in switching losses enable higher switching frequency to be considered which could improve the size and efficiency of systems. WBGs thus offer a significant opportunity to meet 2022 targets (see also Technology Assessment 6.N, Wide Bandgap Semiconductors for Power Electronics). The two most commonly used WBG materials are silicon carbide (SiC) and gallium nitride (GaN). The ability to operate at higher temperatures can decrease system costs by reducing thermal management requirements.

Achieving the 2022 targets for power electronics will require achieving advances in several areas, including device packaging, innovative power module designs, high-temperature capacitors, and new inverter architectures. Device packaging and innovative power module designs can eliminate existing interface layers and provide cooling at or very near the heat sources. Improved capacitors can reduce inverter cost and volume, improve reliability, and enable higher temperature operation. New inverter architectures can reduce part counts and enable modular, scalable components.

The WBG Hub, a consortium of 18 companies and 6 universities led by North Carolina State University and partnering with the federal government, is a manufacturing innovation institute for next generation power electronics.[36] Oak Ridge National Laboratory (ORNL) is leading research in wide bandgap integration, device packaging, and innovative power module designs.[37] Researchers at the National Renewable Energy Laboratory (NREL) are focused on improving thermal management and reliability of power electronics.[38] Industry co-funded research is ongoing in the areas of advanced inverters (including WBG devices) and high temperature, low cost capacitors. There is a need to improve designs while maintaining common manufacturing processes that allow for mass production and do not incur the need for costly equipment and process changes.

Electric Motors

EDT research activities include improving electric motors, with a particular focus on reducing the use of rare earth materials inside the rotor magnet since the magnets account for the largest portion of the motor costs but are essential to meeting the performance targets. The activity's primary goal is to decrease the electric motor's cost, volume, and weight while maintaining or increasing performance, efficiency, and reliability. To meet 2020 cost targets, research must reduce the cost of the motor by 50%.

To achieve these goals, EDT research avenues include the following.

- The Beyond Rare Earth Magnets (BREM) R&D project led by Ames Laboratory is investigating lower-cost permanent magnets and magnetic materials.[39] This effort is closely coordinated with the Critical Materials Institute also led by Ames Laboratory.
- ORNL and industry projects are pursuing reduced rare-earth magnet motors, non-permanent magnet motor designs, and innovative motor materials and designs.
- NREL is focusing research on improving electric motor performance and reliability, and improved thermal management for electric motors and power electronics.[40]

Vehicle Systems

Vehicle Systems provides an overarching systems perspective in support of the technology R&D. Vehicle Systems uses analytical and empirical tools to model and simulate potential vehicle systems, validate component performance in a systems context, verify and benchmark emerging technologies, and validate computer models. Hardware-in-the-loop testing allows components to be controlled in an emulated vehicle environment. Laboratory testing provides measurement of progress toward DOE technical goals and eventual validation of DOE-sponsored technologies at Argonne National Laboratory's Advanced Powertrain Research Facility (APRF), Oak Ridge National Lab's Vehicle Systems Integration (VSI) Laboratory, and at the National Renewable Energy Lab's ReFUEL Facility. The activity's success relies on extensive collaboration with the technology development activities within the VTO and the Fuel Cell Technologies Office (FCTO) for both analysis and testing. Analytical results of this program are used to estimate national benefits and/or impacts of DOE-sponsored technology development.

Figure 8.E.17 Activities Integration for Vehicle System Simulation and Testing (arrows represent information flow between activity focus areas that enhances effectiveness of individual activities)[41]

Credit: Argonne National Laboratory

Figure 8.E.17 presents Vehicle Systems focus areas and their brief descriptions. A detailed technology development roadmap has been developed by DOE and industry partners.[42]

- **Modeling & Simulation:** VISION,[43] NEMS,[44] MARKAL,[45] and GREET[46] are software tools developed by DOE and used to estimate national-level energy, environmental, and economic parameters including oil use, market impacts, and greenhouse gas contributions of new technologies. These estimates are based on VTO vehicle-level simulations that predict fuel economy and emissions using Vehicle Systems' Autonomie[47] modeling tool. Autonomie's simulation capabilities allow for accelerated development and introduction of advanced technologies through computer modeling rather than through expensive and time-consuming hardware building. Modeling and laboratory and field testing are closely coordinated to enhance and validate models. Autonomie is a MATLAB-based software environment and framework for automotive control system design, simulation, and analysis. This platform enables dynamic analysis of vehicle performance and efficiency to support detailed design, hardware development, and validation.
- **Vehicle Technology Evaluations:** This work benchmarks automotive technology progress using structured and repeatable testing methods in the laboratory as well as in real world fleet testing. This effort provides unbiased, independent, public, quality data on advanced technologies for analysis and decision making, to quantify performance targets, and to develop and validate simulation models. The main activity is the Advanced Vehicle Testing Activity managed by the Idaho National Laboratory (INL). Several advanced technology vehicles are purchased to undergo baseline performance testing at the track and in the laboratory before being placed in a fleet. The vehicle instrumentation is used to provide a regular analysis report for each vehicle in the fleet. Other activities include the evaluation of climate control load reduction at NREL and charging infrastructure evaluations across several national laboratories.
- **Codes and Standards:** This work supports the development and adoption of codes and standards for PEVs. Many experts at the national laboratories lead and serve on committees which develop standards that address communications, interoperability, security, safety, performance of PEVs and charging infrastructure, and end-of-life issues such as battery recycling or secondary use. DOE identifies gaps in technology and recommends enabling solutions through creation of proof-of-concept hardware/

software and validation of approaches. Coordination and harmonization is needed among different domestic entities as well as internationally to enable successful PEV adoption.

- **Vehicle Systems Efficiency Improvements:** Research also focuses on investigating systems optimization strategies and enabling technologies to enhance vehicle efficiency, robustness, and emissions performance. Some of the main research areas relevant to PEVs include aerodynamic drag reduction, friction and wear reduction, thermal control and auxiliary load reduction, fast and wireless charging, and Smart Grid Integration.

DOE also champions the workplace charging challenge under Vehicle Systems activities. Many PEV drivers charge their vehicles primarily at home, but accessing chargers at work can help owners double their PHEV's all-electric daily commuting range.

As part of the greater DOE Grid Modernization crosscut, Vehicle Systems identifies and addresses challenges associated with the large-scale deployment of PEVs on the electric grid, and maximizes the opportunities that PEVs represent when integrated with other distributed clean energy resources. The Vehicle Systems activity works to identify what services PEVs may provide to the electric grid, and quantify the multiple value streams associated with these services when fully integrated with distributed solar generation, building energy management systems, and other smart grid technologies. Additionally, the activity supports the development and demonstration of new devices (e.g., low-cost communications-capable energy meters), systems, and algorithms to enable advanced control of PEVs across the electricity distribution system.

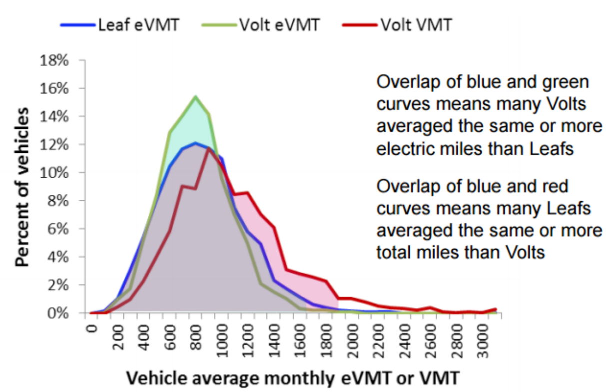
Data Collection Insights from the EV Project

Under the ARRA co-funded EV Project, data collected from October 1, 2012 through December 31, 2013 on nearly 6,000 PEVs (see Figure 8.E.18 - left) showed that the Nissan Leaf (BEV) accumulated only 6% more electric vehicle miles traveled (eVMT) per month compared to the Chevrolet Volt (PHEV). The distribution of vehicle average monthly eVMT and VMT, where each data point in the distributions represents a single vehicle's average over the entire study period is shown on the right in Figure 8.E.18. With a gasoline engine backup in the PHEV after the battery is depleted, the Volt drivers frequently maximized their all-electric miles available while the Leaf drivers very seldom neared emptying the battery to prevent getting stranded.

Figure 8.E.18 Nissan Leaf (BEV) vs. Chevrolet Volt (PHEV) Average Monthly eVMT Comparison[48]

Credit: Idaho National Laboratory

	Nissan Leaf	Chevrolet Volt
Number of vehicles	4,039	1,867
Number of vehicle months	35,294	20,545
Total distance traveled (miles)	28,520,792	20,950,967
Distance traveled in EV mode (miles)	28,520,792	15,599,508
Percent of distance traveled in EV mode	100%	74.5%
Average monthly total VMT	808.1	1,019.8
Average monthly eVMT	808.1	759.3

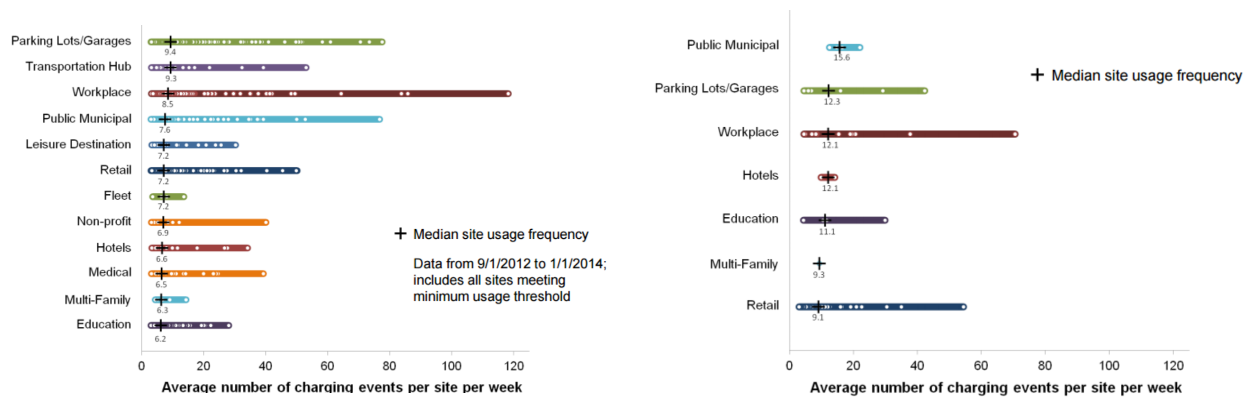


Distribution of vehicle average monthly eVMT and VMT, where each data point in the distributions represents a single vehicle's average over the entire study period.

Figure 8.E.19 shows the average number of weekly PEV charging events for different venues where the charging stations were installed under the EV Project. The left side of the figure has data for the more common Level II (240V alternating current) charging stations and the right side shows the DC fast charger (DCFC) data (480V direct current). While the range of weekly charging events varied significantly within each of the charging venues, the median site usage frequency was relatively consistent among the different venues showing that there is a lot more to the successful placement of public PEV charging infrastructure than just the venue type.

Figure 8.E.19 Distribution of Usage Frequency of the EV Project Level 2 (left) and DCFC (right) Charging Stations by Venue[49]

Credit: Idaho National Laboratory



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Acronyms/Glossary

ANL	Argonne National Laboratory
APRF	Advanced Powertrain Research Facility
ARPA-E	Advanced Research Projects Agency – Energy
ARRA	American Recovery and Reinvestment Act
BatPaC	Battery Performance and Cost model
BEV	Battery electric vehicle
BREM	Beyond Rare Earth Magnets
CAFE	Corporate Average Fuel Economy
CI	Compression-ignition internal combustion engine
CNG	Compressed natural gas
CO_2	Carbon dioxide
DC	Direct current
DCFC	Direct current fast charger
DOE	Department of Energy
EDT	Electric drivetrain
EM	Electric motor
EV	Electric vehicle
eVMT	Electric vehicle miles traveled
FC	Fuel Cell
FCTO	Fuel Cell Technologies Office
GaN	Gallium nitride
GHG	Greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use model
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
INL	Idaho National Laboratory

JCESR	Joint Center for Energy Storage Research
kW	Kilowatt
kWh	Kilowatt-hour
Li	Lithium
LMRNMC	Lithium- and manganese-rich high-energy cathode
MARKAL	Market Allocation model
NEMS	National Energy Modeling System
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PEV	Plug-in electric vehicle
PHEV	Plug-in hybrid electric vehicle
PM	Permanent magnet
R&D	Research and development
SI	Spark-ignition internal combustion engine
Si	Silicon
SiC	Silicon carbide
SOC	State of charge
UDDS	Urban Dynamometer Driving Schedule, which simulates urban driving conditions during emissions and fuel economy tests
USABC	United States Advanced Battery Consortium
VMT	Vehicle miles traveled
VSI	Vehicle Systems Laboratory
VTO	Vehicle Technologies Office
W/m^2	Watts per square meter
W/kg	Watts per kilogram
Wh/kg	Watt-hours per kilogram
WBG	Wide bandgap