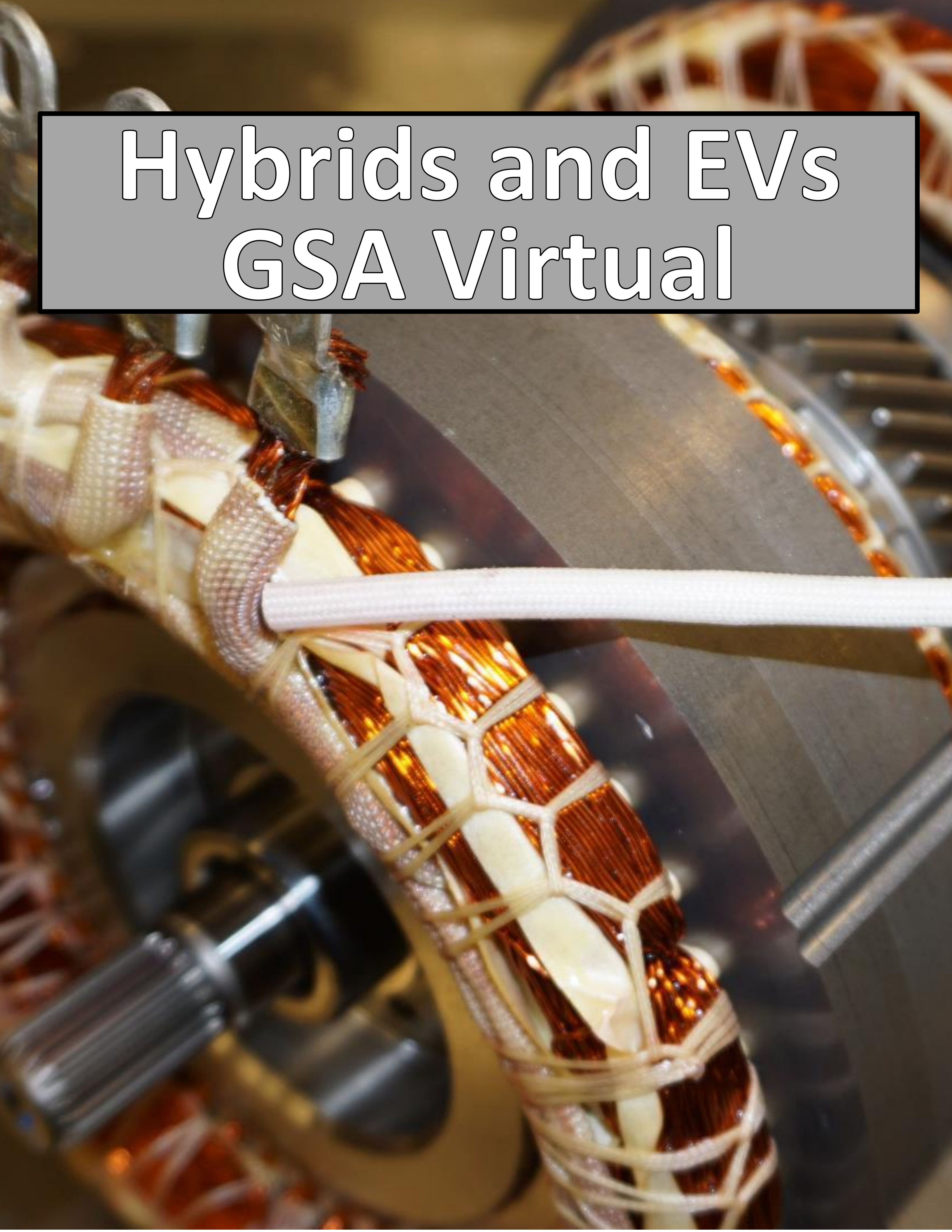
Hybrids and EVs GSA Virtual



Contents

0 – Results from a previous GSA survey

A few years ago, we asked GSA for a summary of topics they'd like discussed during EV training. The following were the common topics:

1. **What's the benefit of a hybrid or an EV?**

2. **How are xEVs configured?**
   - During this presentation, we'll cover
     a. *Hybrid*
     b. *Parallel*
     c. *Series*
     d. *Series/Parallel*
     e. *Full hybrid vs. mild hybrid*
     f. *Plug-in Hybrid*
     g. *EV*

3. **What makes them different?**
   - During this presentation, we'll cover:
     a. *Engine*
     b. *Electric motor*
     c. *Inverter Technology*
     d. *Cooling system*
     e. *Battery*
     f. *High voltage*
     g. *Low voltage*
     h. *Charging*
     i. *Braking System*
     j. *Regenerative Braking*
     k. *AC/Heating System*

4. **What are some service considerations?**
   - During this presentation, we'll cover:
     a. *Hybrids engines are similar to conventional vehicles*
     b. *Oil changes*
     c. *Spark plugs*
     d. *Air filter*
     e. *Cooling system*
     f. *Brake systems*
     g. *Tire rotation/Balancing*
     h. *Cooling system maintenance*

5. **What are some usage considerations?**
   - During this presentation, we'll cover:
     a. *Towing requirements*
     b. *Charging requirements*
     c. *Practicality*
     d. *Management*
     e. *Recycling*

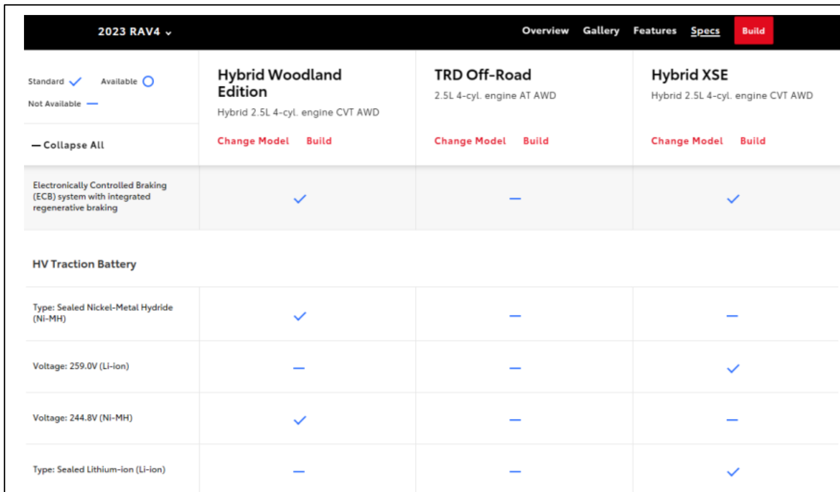
1 - Introduction

What is the “x” in xEV? Electrified vehicles come in various forms, such as hybrid (HEV), plug-in Hybrid (PHEV), and full battery electric (BEV). Most of the technology, generically speaking, is the same between these three forms. As you will see in section three, most HEVs, PHEVs, and BEVs all utilize a high-voltage battery, power inverter, DC-DC converter, and one or more electric motors. Instead of covering these vehicles as if they are unique to each other, this resource includes them all and designates the “x” as the variable. An xEV could potentially be a HEV, PHEV, or BEV.

The turning point for EV adoption was the refinement of the Lithium-Ion battery. The Li-ion battery has a very high energy density, high specific power, and a great cycle life. Once the lithium battery was introduced into a full BEV, the advantages and capabilities were soon realized.

Before the li-ion battery, Nickel Metal Hybride batteries (NiMH) were used in xEVs and offered a few of the same advantages. The NiMH battery allowed the hybrid vehicles of the early 2000s to supplement the ICE during acceleration, starting, and low-speed driving. The NIMH battery was small enough to tuck away behind or under a seat or in the trunk area, but large enough to recoup energy during regenerative braking. For this reason, NiMH batteries are still used in Toyota Hybrid vehicles. The battery technology is still relevant for certain applications, although most manufacturers have evolved to the lithium battery.

The applications have also changed in the past couple of decades. New hybrid designs are available that allow for increased efficiency. The plug-in hybrid allows for short EV-only driving, then an ICE takes over propulsion. The BEV is now available as a compact car, sedan, SUV, and Truck. Most segments of the automotive market are represented by ICE, Hybrid, and BEV vehicles.



2023 RAV4 ⌄ Overview Gallery Features Specs Build

Standard ✓ Available ○ Not Available — / — Collapse All	Hybrid Woodland Edition Hybrid 2.5L 4-cyl. engine CVT AWD Change Model Build	TRD Off-Road 2.5L 4-cyl. engine AT AWD Change Model Build	Hybrid XSE Hybrid 2.5L 4-cyl. engine CVT AWD Change Model Build
Electronically Controlled Braking (ECB) system with integrated regenerative braking	✓	—	✓
HV Traction Battery			
Type: Sealed Nickel-Metal Hydride (Ni-MH)	✓	—	—
Voltage: 259.0V (Li-ion)	—	—	✓
Voltage: 244.8V (Ni-MH)	✓	—	—
Type: Sealed Lithium-ion (Li-ion)	—	—	✓

Toyota Rav4 offers NiMH in 2023. Other vehicles in 2023 with NiMH include the Sienna, Crown, Tundra, and Sequoia

The following are common characteristics of an xEV.

Hybrid vehicle characteristics

- Operator does nothing different than with an ICE vehicle
- Start/stop features offer smoother and quieter engine operation due to an electric motor instead of a gear drive starter motor
- Smaller high-voltage and 12V battery
- No range issues, better fuel economy over an ICE vehicle, typical fueling experience
- 2-5k upcharge over an ICE vehicle

Plug-in Hybrid Vehicle Characteristics

- Operator can opt to do nothing, but plugging the vehicle in will allow for EV-only operation for a relatively short distance
- Europe studies show that many owners don't plug in, which makes the vehicle less efficient since there's added weight associated with the larger PHEV battery [real-world-phev-use-jun22-1.pdf (theicct.org)]
- When in hybrid mode, start/stop features offer smoother and quieter engine operation due to the electric motor instead of a gear drive starter motor
- No range issues, better fuel economy, and typical fueling experience
- 5-10k upcharge over an ICE vehicle

Battery Electric Vehicle (BEV)

- Operator charges vehicle at home or an EV charging station
- Home charging is preferred for lower costs, no fuel station visits
- Potential range issues if traveling long distances. Drivers need to consider the location of charging stations. Limited charging networks may force drivers to reroute to ensure access to charging stations.

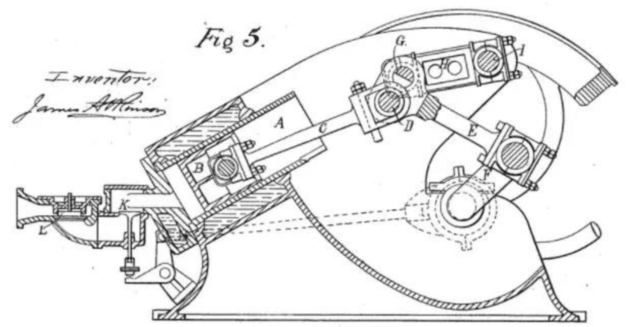
Energy recovery

The major benefit of an xEV is the ability to store the energy used to decelerate the vehicle as chemical energy in a battery. Normally, in a traditional vehicle, all energy used to decelerate is lost through friction and heat. With an xEV, the traditional hydraulic brakes are only used during heavy braking or when the vehicle is traveling too slow to effectively generate enough resistance through the electric motor(s). Most of the braking is accomplished by the energy produced when the electric motors generate electricity. The braking system is covered in more detail in section eight. When the driver decelerates, the electronic control system will want to take full advantage of the regeneration and not use any hydraulic braking. This action needs to be seamless and feel consistent for

The "brake coach" on the Ford Fusion lets the driver maximize their regenerative braking.

the driver, so xEVs have an advanced braking system to ration the hydraulic vs. electrical regeneration as needed.

Efficient ICE Engines



Atkinson engine design from 1882

HEV and PHEV vehicles also take advantage of an engine technology that has been around for a century but was never really used in traditional ICE vehicles until hybrid vehicles came about. The conventional engine's four-stroke cycle is modified to operate with a pseudo "Atkinson cycle." This design never gained popularity because it had less power output when compared to an equal-sized Otto-cycle engine, even though it was more fuel efficient. The adoption of the HEV/PHEV allows for the use of this engine since it's coupled with an electric drive motor, which produces excellent low RPM torque.

If you search up the actual Atkinson cycle engine, you'll see it's quite a contraption that had links on the crankshaft and connecting rods that physically altered the piston movement during the four-stroke cycles. The goal is to decrease the length of the intake and compression stroke and increase the length of the power (or expansion) stroke. This concept is carried over to the *modified* Atkinson cycle engine that keeps the intake valve open during much of the compression stroke. This results in an engine that generates a lower intake vacuum and a shorter "effective" compression ratio. The compression ratio is defined as how much air/fuel is being compressed when the piston is at BDC vs. TDC. A 10:1 would signify that the volume was reduced 10 times. Since the Atkinson cycle engine closes the intake valve much later in the compression stroke than a typical ICE, the <u>effective</u> compression ratio begins when the cylinder is sealed and with the Atkinson design, the piston is already high in the cylinder.

Unlike the true Atkinson engine design, the intake and compression stroke aren't reduced, but through valve control, the intake stroke extends long enough into the compression stroke that it pushes air/fuel back into the intake, and when the intake valve is finally closed, the compression stroke is much shorter than it would be with a conventional ICE. This feature improves the thermal efficiency of the engine and reduces the pumping losses. Pumping losses exist because only one stroke of the four-stroke cycle engine actually contributes to output power -the power (expansion) stroke. The compression stroke works against rotation because it's building pressure. The intake stroke works against engine rotation because it creates suction (negative pressure). The exhaust stroke resists rotation because of friction. One might notice that the Atkinson cycle engines have a published high compression ratio, but the effective compression ratio is much lower because the intake valve remains open during much of the compression stroke, so the piston is not building pressure during that period.

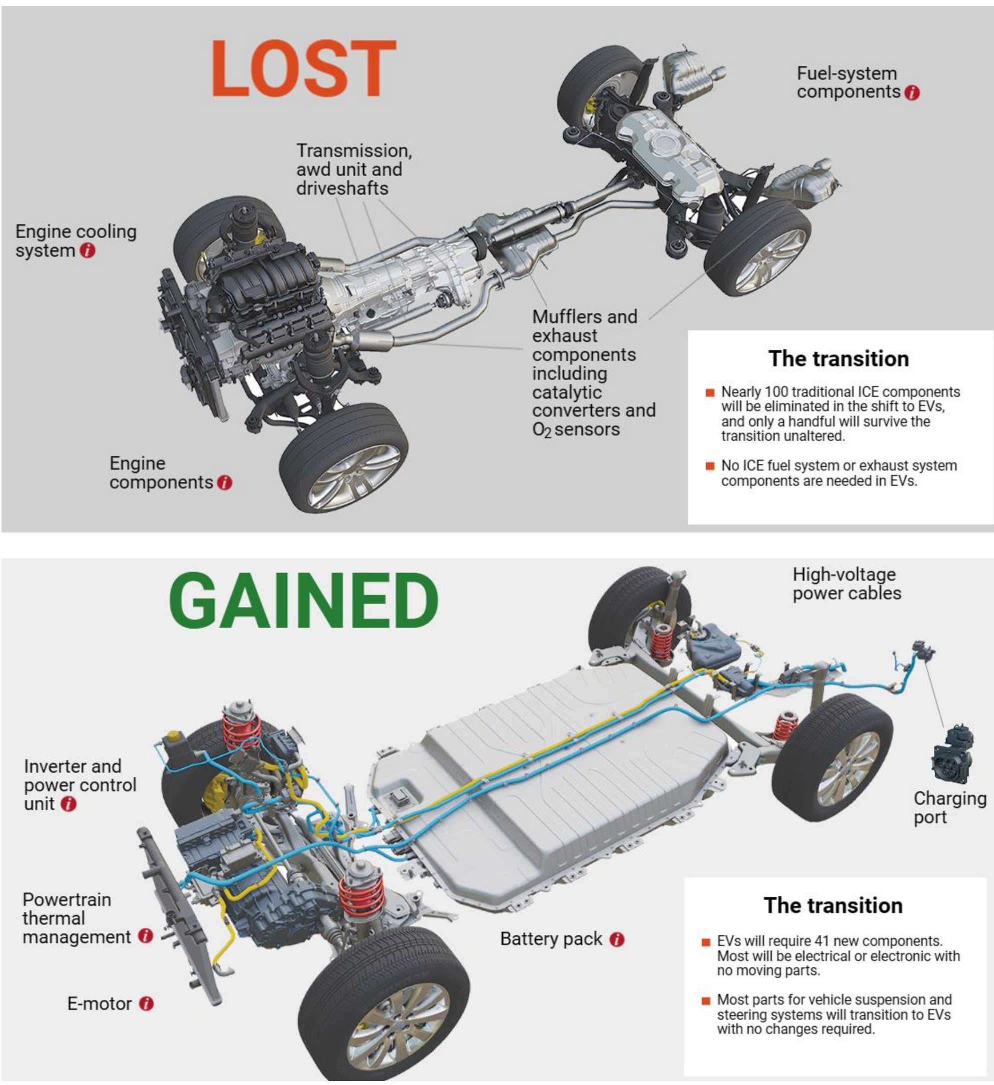
As Honda explains in the news release for the 2023 CR-V Hybrid,

> *"The Atkinson cycle holds the intake valve open longer than normal during the compression stroke, allowing a reverse flow of intake air into the intake manifold. This allows more complete use of the energy from the combustion process, greatly enhancing efficiency. As a result, each engine paired with the two-motor hybrid system has been among the most thermally efficient gasoline*

engines ever used in a mass-production vehicle, with a thermal efficiency of around 40%, compared to the 25% to 30% thermal efficiency of most combustion engines." [Honda Two-Motor Hybrid-Electric System (hondanews.com)](hondanews.com)

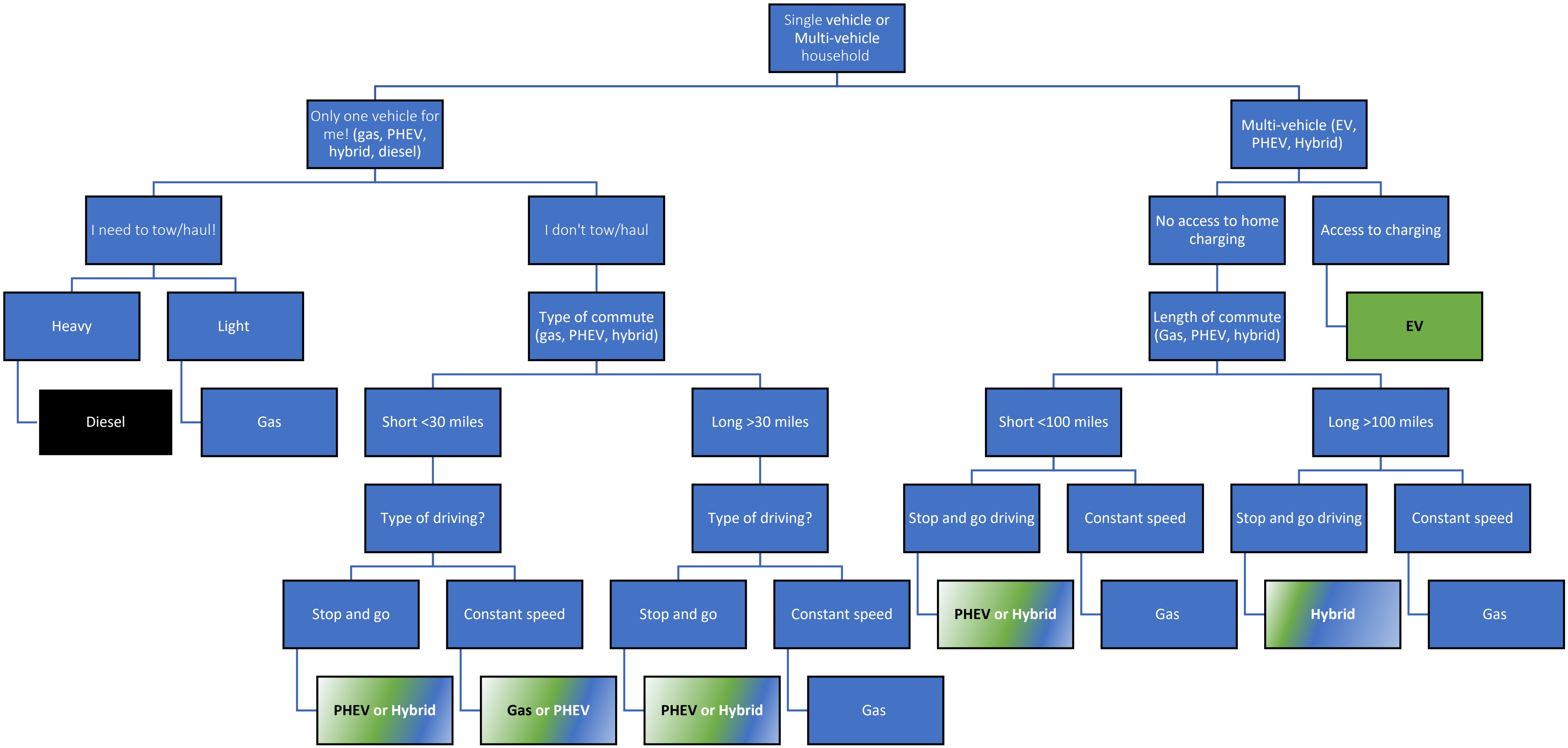
Parts reduction

For obvious reasons, the BEV doesn't benefit from engine technology like a HEV/PHEV, but the BEV is reported to have about 15,000 fewer parts than a typical ICE vehicle. Electric motors and their controls are less mechanically complex resulting in fewer parts. They are, however, heavy due to the large battery and are known to wear tires quickly. This is coupled with the fact that battery materials are commonly sourced from countries that don't take part in the US fair trade. Whether a traditional gas or diesel vehicle or an xEV is most practical for the consumer is not an easy question to answer.

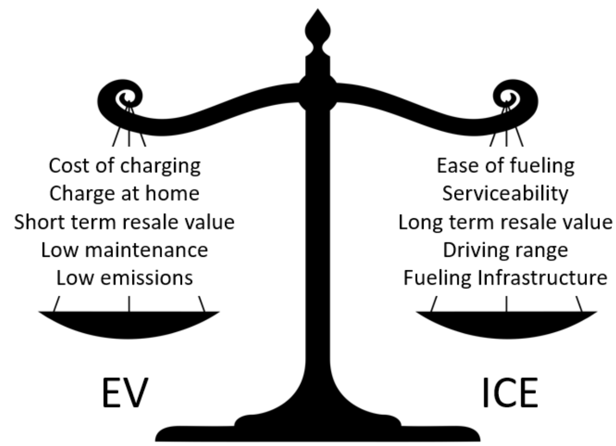


Comparison from autonews.com

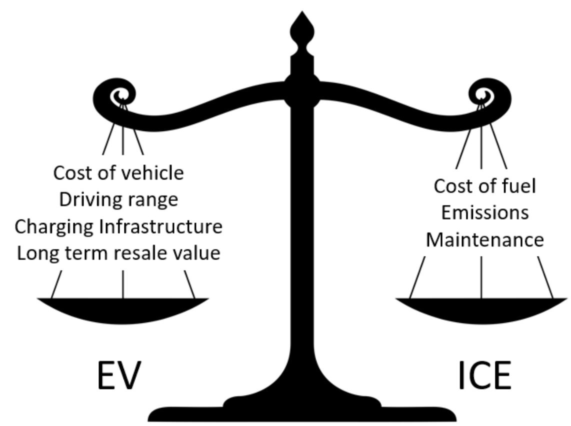
What's best for me?



EV vs. ICE Advantages



EV vs. ICE Disadvantages



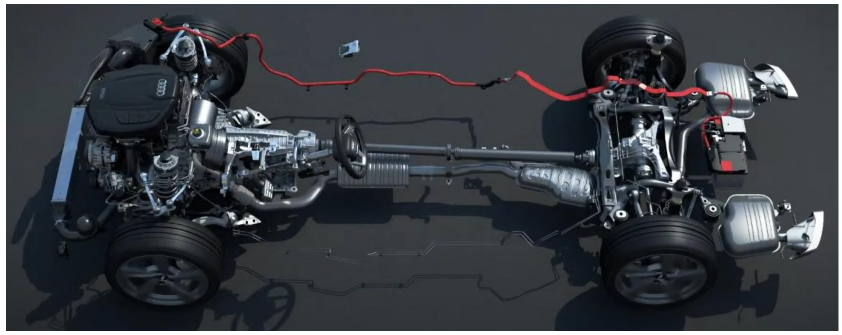
xEV Vehicle Configurations

Hybrid (HEV)

How the vehicle's powertrain is designed will ultimately define the hybrid vehicle's configuration and classification. A hybrid vehicle is commonly classified as either a mild or full hybrid. The classification level is based on the operating voltage, powertrain configuration, and the level of fuel economy improvement.

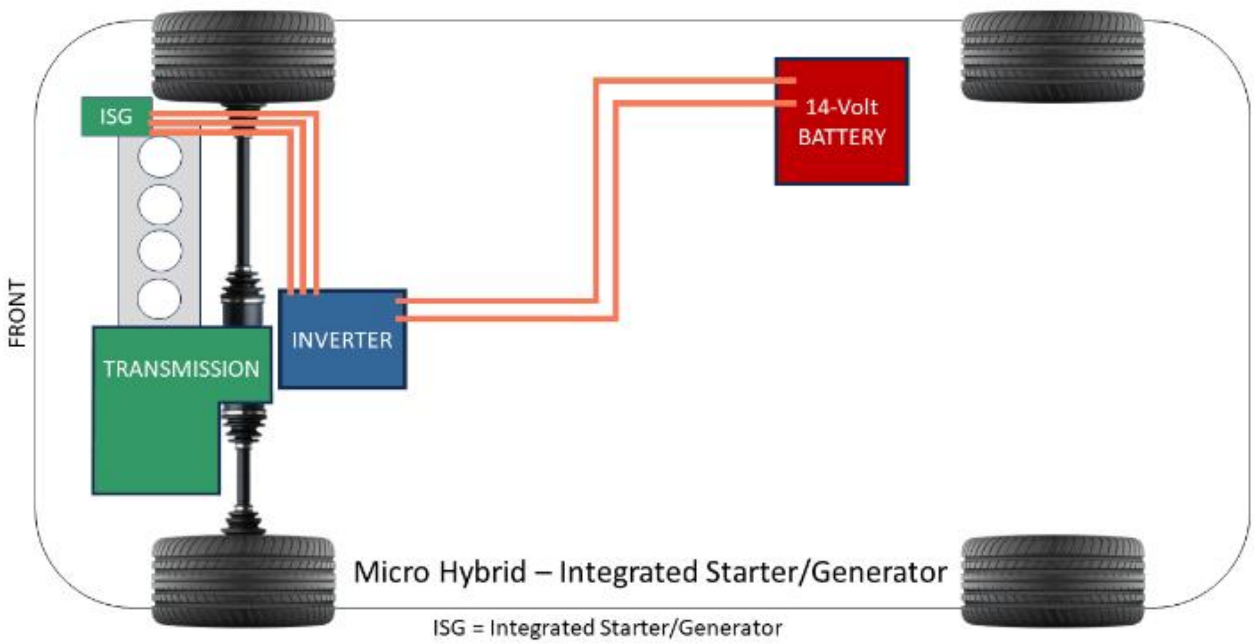
Please note, that there are many different interpretations of hybrid classifications. Rarely do you see a manufacturer refer to their system as a micro, mild, medium, or full hybrid. In the US, many government agencies consider mild hybrid systems as vehicles that are 48 volts or less, have smaller electric motors, and therefore offer lower fuel economy improvements. Many sources of information label these types of hybrids as "micro," and these sources refer to mild as a system with a medium-sized motor that assists the internal combustion engine but doesn't offer many of the advantages of a full-hybrid. At times, a vehicle may be classified as a micro-hybrid if the vehicle only uses the 12-volt system but has many of the characteristics of a typical mild hybrid system. The following are characteristics of these three classifications, but overlap may exist.

Micro Hybrid – A "start/stop" vehicle with an integrated starter/generator is commonly classified as a micro-hybrid. The engine automatically shuts off at a stop and restarts when the driver releases the brake pedal. The alternator can provide additional load to the powertrain for regenerative braking purposes, which allows some of the braking energy to be stored in a low-voltage battery. The micro-hybrid still uses the conventional 12-volt system and is estimated to reduce fuel consumption by 3-5%. There are not many vehicles with this configuration in the US. In 2024, the Audi A4 has a 14V Lithium-Ion battery that operates an integrated starter/generator and could be classified as a micro-hybrid.



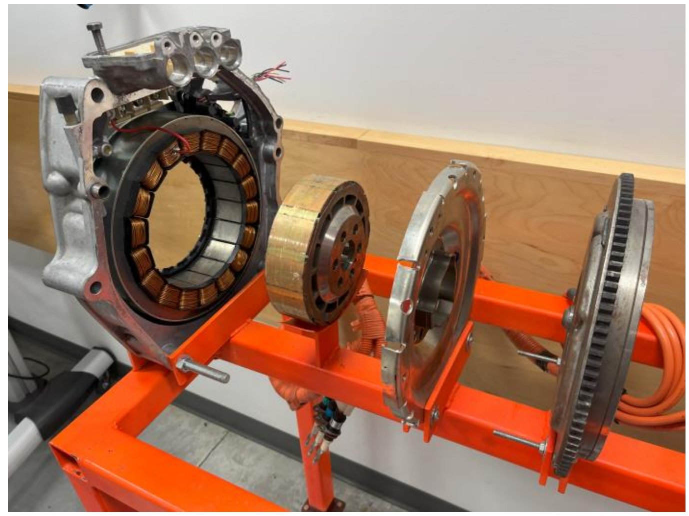
Micro hybrid: Audi A4 14-volt micro hybrid powertrain

[Audi A4 TFSI 12 Volt MHEV Mild Hybrid System Demonstration (youtube.com)]



Mild Hybrid

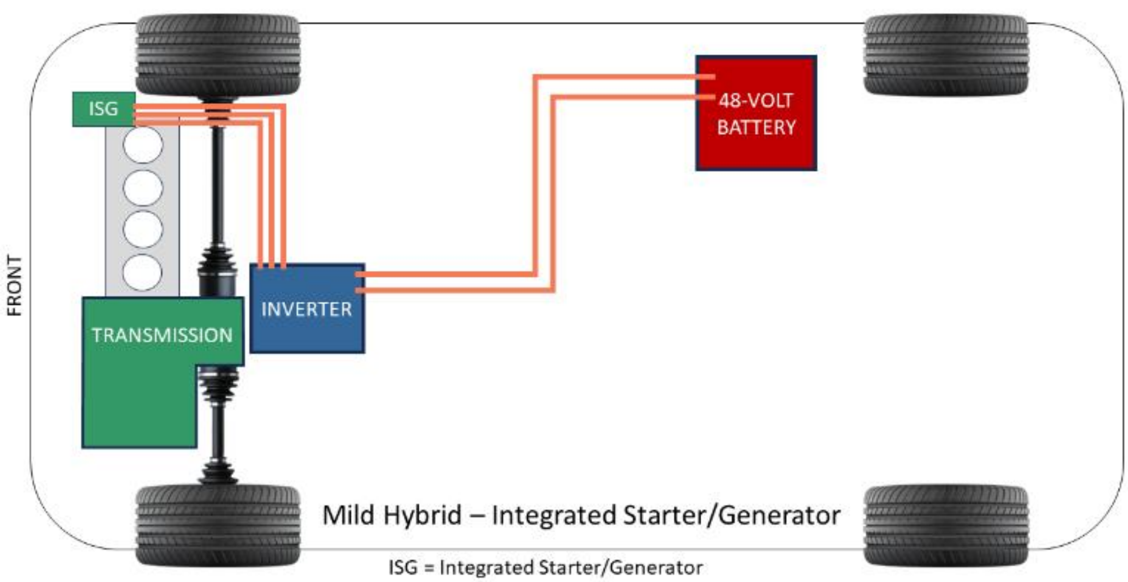
The mild hybrid vehicles can assist the engine during acceleration, use regenerative braking to store braking energy in a medium or high-voltage battery and allow for start/stop of the internal combustion engine. Vehicle configurations vary greatly within the mild-hybrid category. Like a micro-hybrid, a mild-hybrid might use an integrated starter/generator along with a higher-voltage battery, such as a 42- 48 volt or higher voltage battery. Some hybrid vehicles with an electric motor located between the engine and transmission or within the transmission might also be classified as a mild hybrid. The electric motor power output and the battery size play a factor in the mild-hybrid classification. The electric motor is smaller than a full-hybrid and the battery has less capacity. These systems can improve fuel economy by 5 – 10% and provide 10-15KW of power (ZF trans brochure). The Ram/Jeep e-Torque system would fit into this category.



Mild or medium hybrid? This Honda Civic IMA system uses a 144-volt battery and an electric motor housed between the engine and transmission. Would you consider it mild or medium?

There are many advantages to the mild-hybrid design.

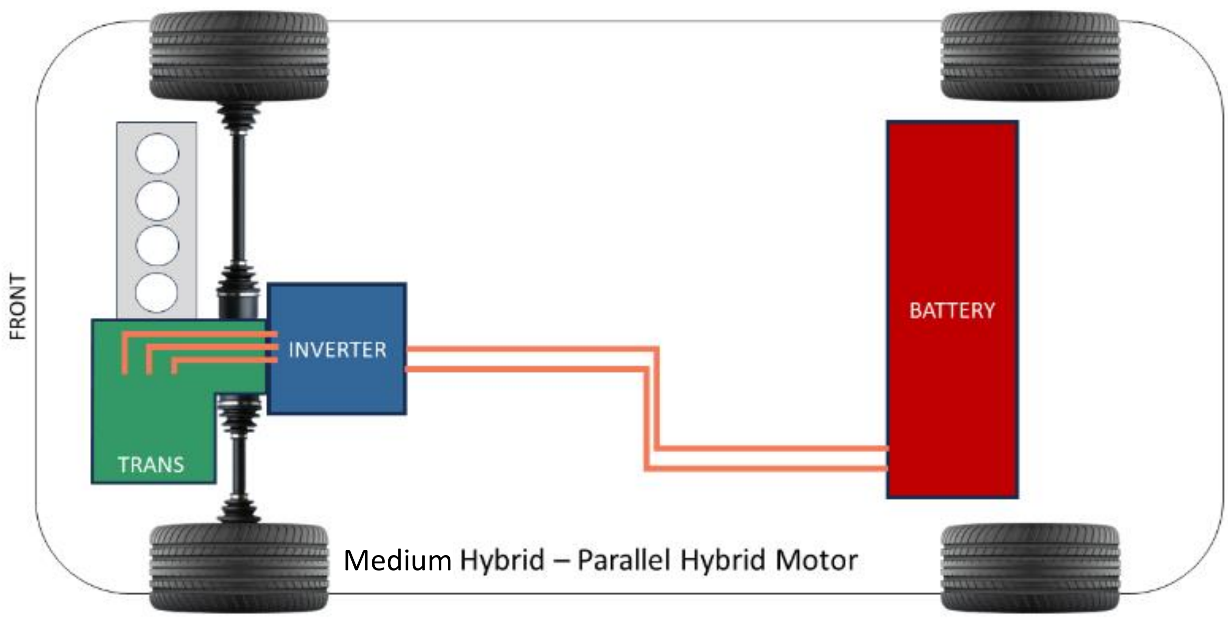
- Adapt current vehicles and technology to use the hybrid technology without a major redesign
- Utilization of lower-capacity batteries
- Enhanced driver satisfaction regarding start/stop



[Audi Tech Defined: MHEV (Mild Hybrid Electric Vehicle) (youtube.com)]

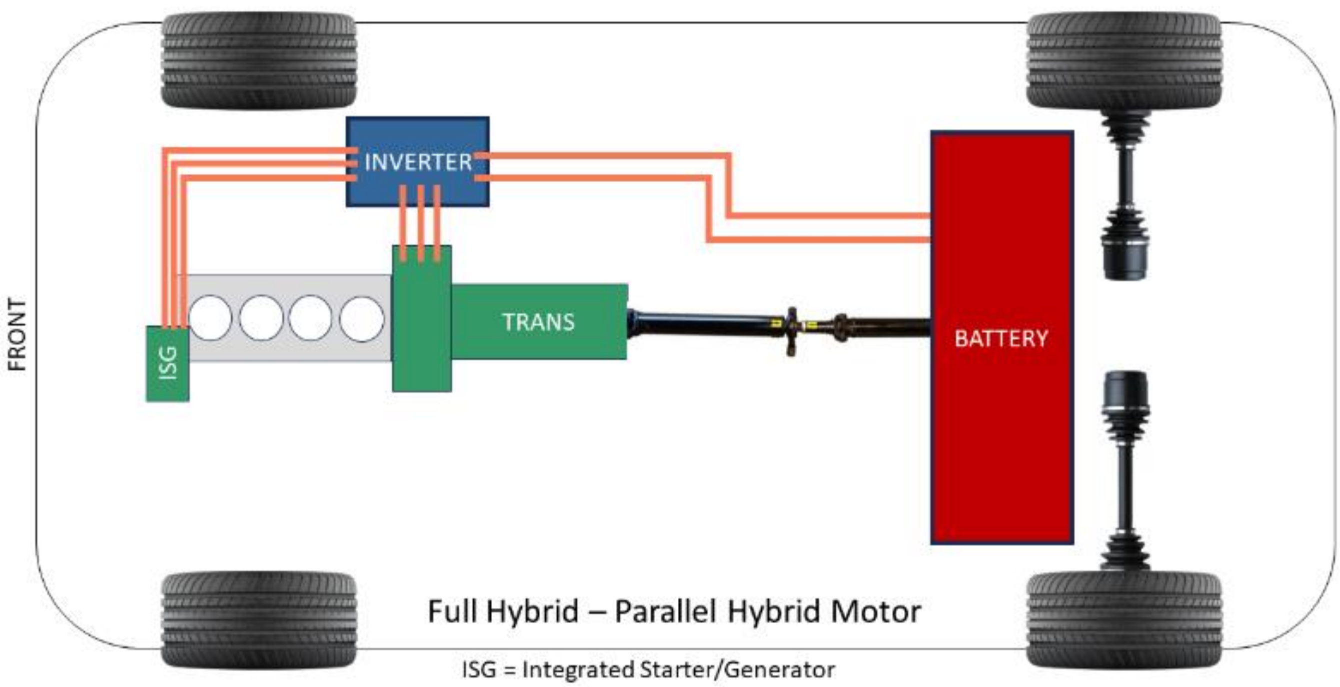
Medium Hybrid

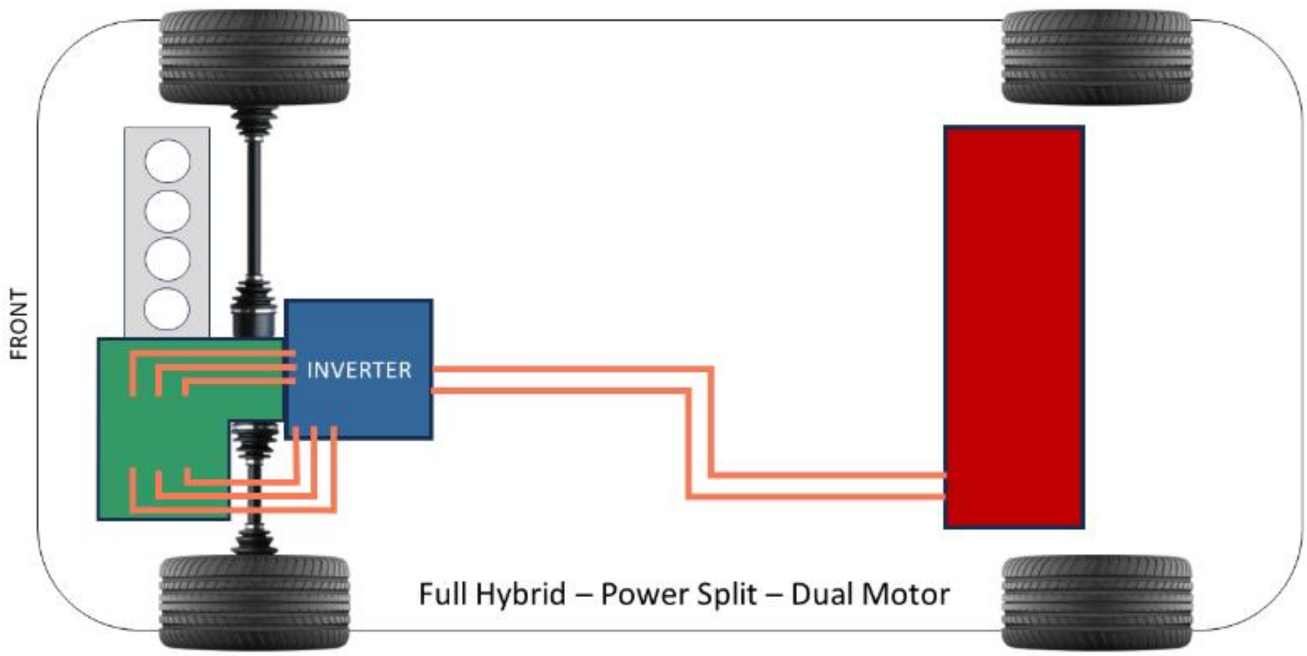
If the hybrid system uses a battery greater than 48 volts, it might be termed a “medium hybrid,” but once again, these classifications seem to vary greatly depending on the source. For example, the early Honda Civic hybrid has a parallel electric motor that is situated between the engine and the transmission. It uses a 144-volt high-voltage battery to power the electric motor. It’s not commonly classified as a full hybrid, but it’s larger than a typical mild hybrid. In these cases, it seems appropriate to define this system as a medium hybrid.



Full Hybrid

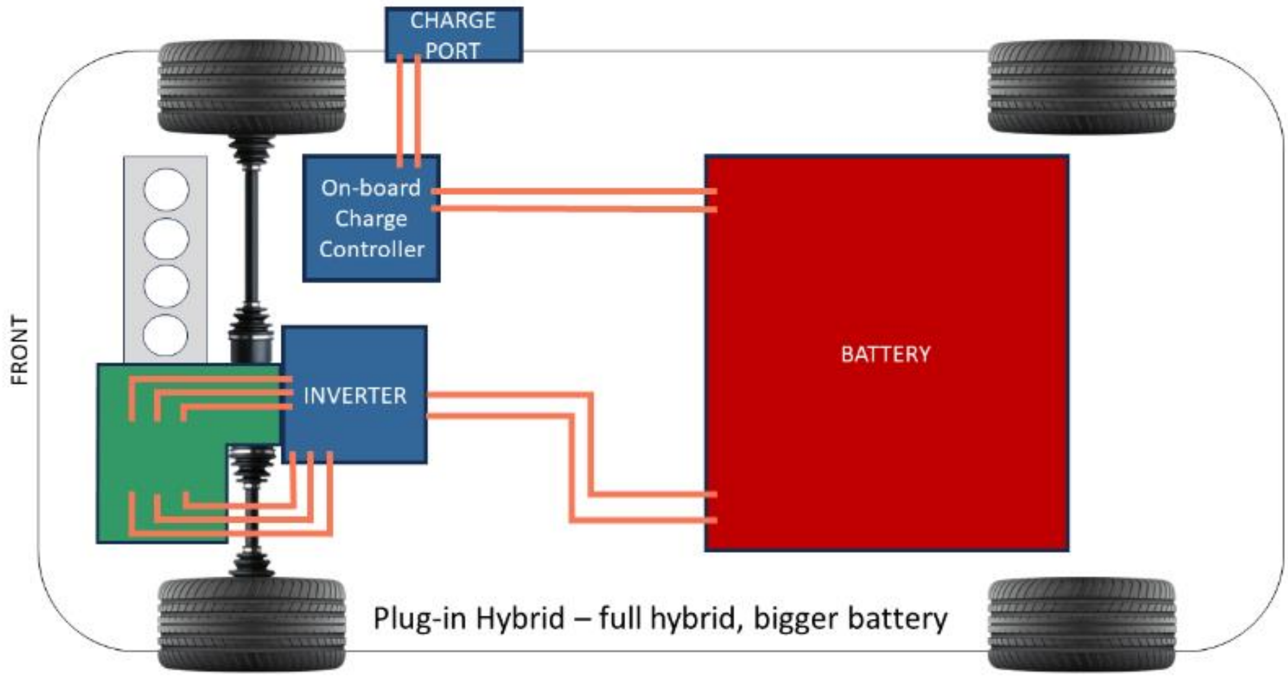
Compared to the mild hybrid, the full hybrid offers a more powerful electric motor (30-100KW) and a higher capacity and higher voltage battery. A full hybrid involves a major redesign of powertrain components to allow for electric motor integration. Typically, the transmission houses one or more electric motors that are responsible for propelling the vehicle and decelerating the vehicle in conjunction with the hydraulic brakes. The full hybrid's transmission, either mechanically or through electric motor control, decouples from the engine to allow for electric-only modes of acceleration and deceleration. This allows the vehicle to take full advantage of regenerative braking because the electric motor can load the driveline to slow the vehicle without having engine friction and compression braking contribute to vehicle deceleration. In a mild hybrid, engine braking, electric motor regeneration, and hydraulic braking work to decelerate a vehicle.




FRONT
INVERTER
Full Hybrid – Power Split – Dual Motor

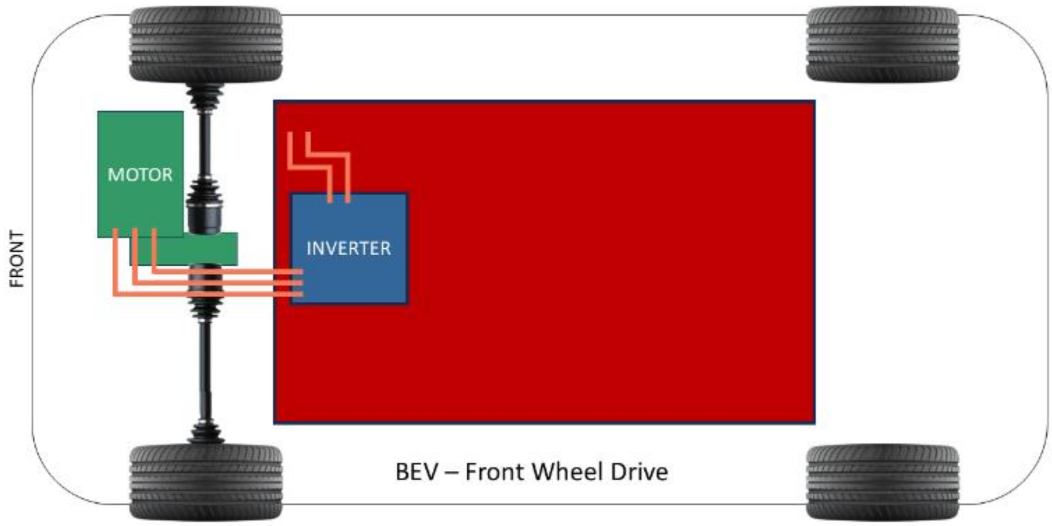
Plug-in Hybrid (PHEV)

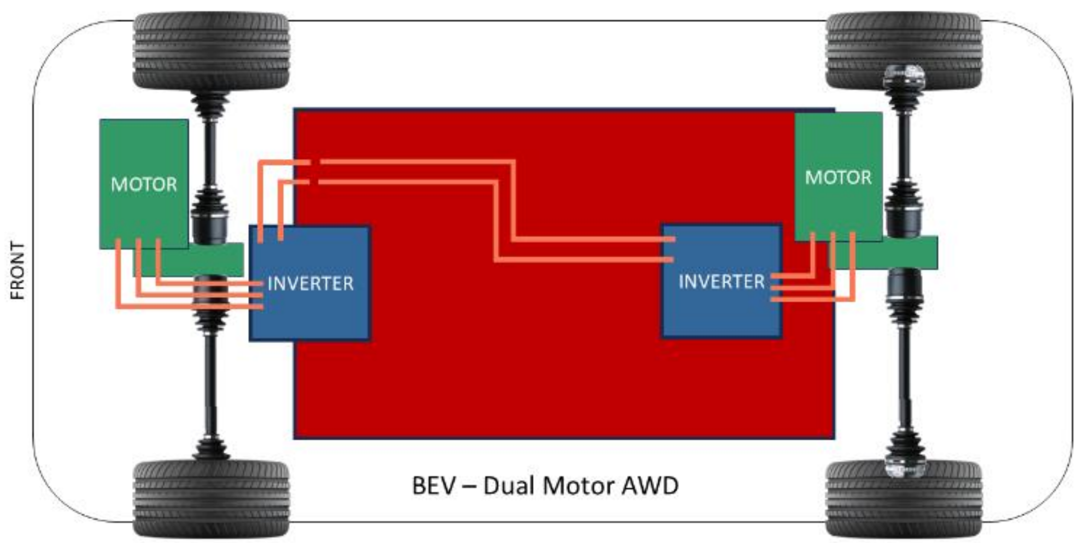
A Plug-in Hybrid vehicle (PHEV) is a full-hybrid vehicle with a larger capacity battery and additional components to allow for charging using standard household utilities (120-240v). Common plug-in hybrid vehicles in the US include the Ford Escape, Toyota Rav-4, Chevrolet Volt, Chrysler Pacifica, and Jeep 4xe. PHEVs are costly because they have all the components of a battery electric vehicle (except a much smaller capacity high-voltage battery) and all the components of an internal combustion vehicle.

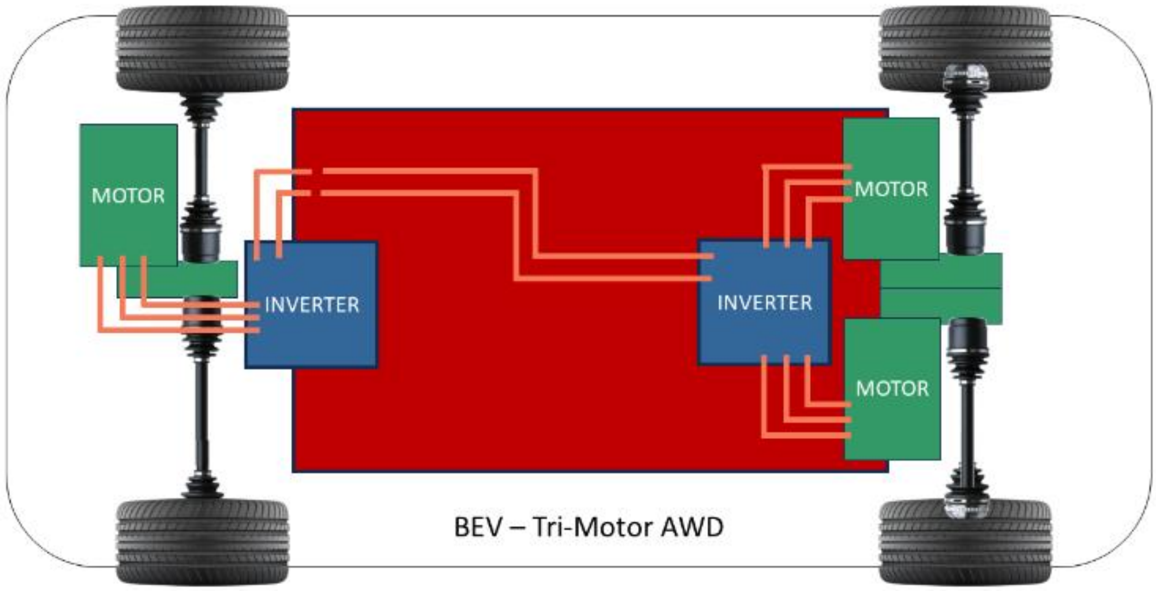


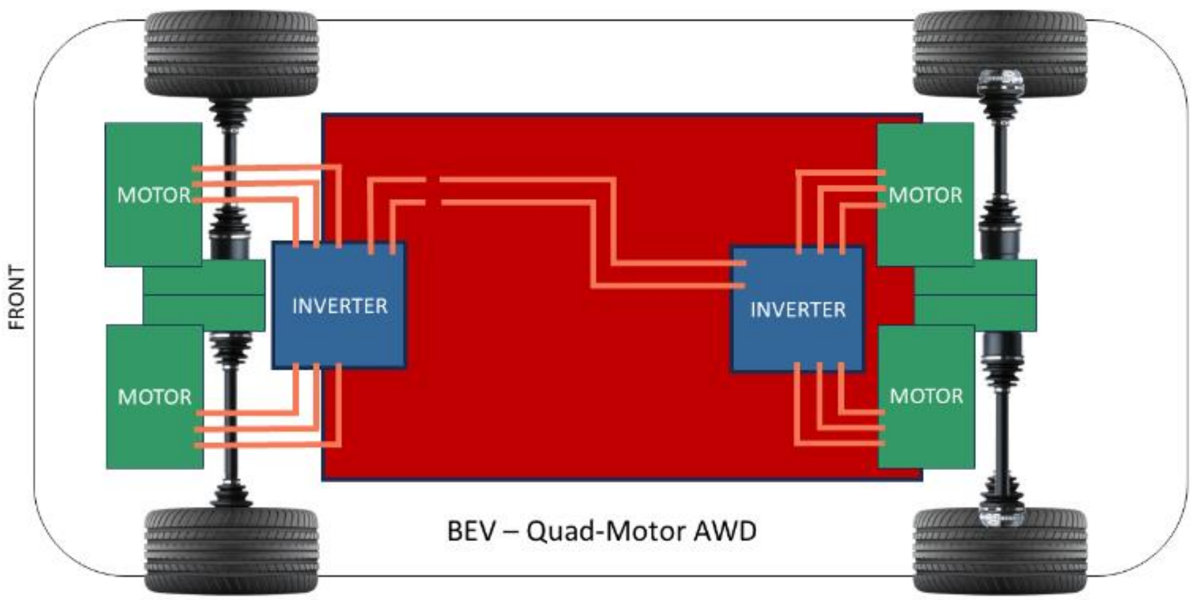
Battery electric vehicle (BEV)

The BEV uses an electric motor to propel the vehicle. There are various configurations, depending on how many motors, the type of motor, and the gear reduction units, but all BEVs contain the same basic components, such as the high-voltage battery, inverter, DC-DC converter, motor, and charging components.









Watch: [eDrive Modular System for Highly Efficient Electric Drives PC - ZF]

High-level Overview

2 - High-level overview

Common principles of operation of an xEV

Assuming the reader has an understanding of the conventional ICE vehicle, it is obvious to most that the internal combustion engine drives a transmission (for gear reduction and overdrive), which feeds a final drive assembly (more gear reduction), which drives the wheels. The vehicle electronics include a 12-volt battery and an engine-driven generator that provides for the vehicle's electronics when the engine is running and also keeps the 12-volt battery charged.

The xEV, depending on the configuration, will share many of these attributes. A HEV or PHEV will still utilize an engine and transmission and final drive. The electric motors will take the place of the generator and they might use their electric motors to control an eCVT, which takes place of the typical step-gear transmission. The HEV/PHEV will still use a final drive to power the wheels.

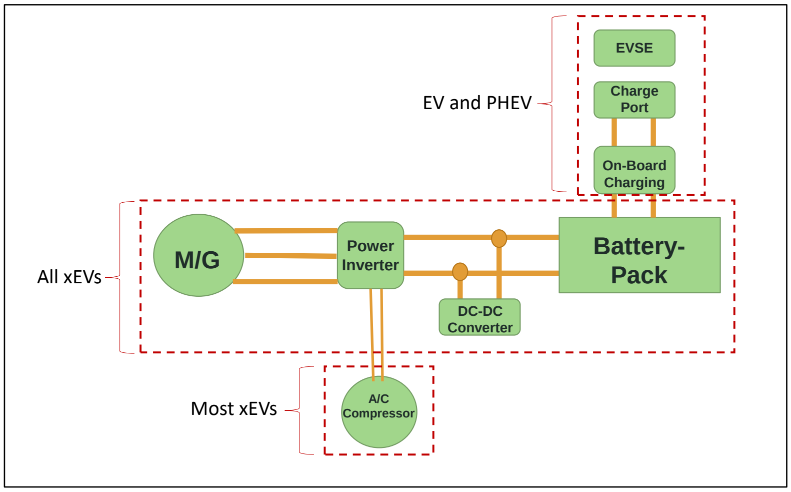
A BEV is much different. Instead of an engine, there's an AC electric motor. With most applications, there is no transmission, since many electric motors can handle 10,000rpm or more (with a new goal of 20,000rpm). The BEV still uses a final drive, or gear reduction unit, to increase torque to the wheels. The BEV fundamentally is a much simpler vehicle, since the electric motor replaces the traditional ICE vehicle's engine and transmission.

Components	ICE	HEV	PHEV	BEV
Engine	X	X	X	
Emissions components	X	X	X	
Fuel tank	X	X	X	
HV Battery		X	X	X
Transmission	X	X*	X*	
Electric Motors		X*	X*	X
Inverter		X	X	X
DC-DC Converter		X	X	X
Elect AC		X	X	X
Charge controller			X	X
Charge port			X	X

* - transmission and electric motors might be combined to create an eCVT.

Regardless of make or model, all xEVs use the following components:

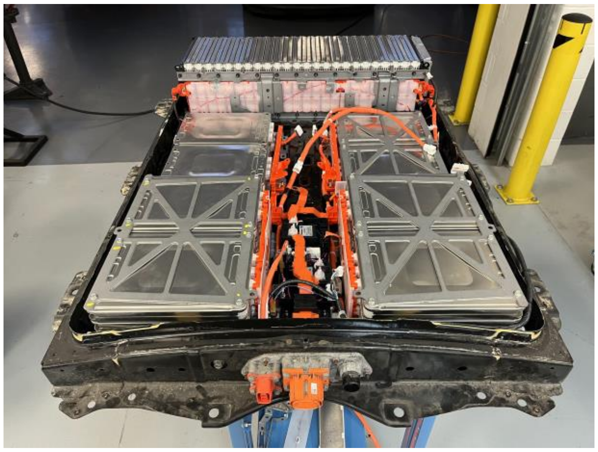
Low-voltage battery



Like a conventional ICE vehicle, the low voltage system powers most of the vehicle's components, including the various modules, lighting, communication system, interior convenience such as power windows, door locks, audio system. Most vehicles use a standard 12v lead-acid battery that can be tested with the common shop equipment. In the early 2020's, some vehicles have adopted a lithium-ion low voltage battery. These systems operate at a slightly higher voltage that a lead acid battery. This is due to the cell voltage from an individual lithium-ion battery and the combination of cells used in the vehicle's low voltage. Many lithium-ion chemistries have about four volts per cell when fully charged, so a series circuit of four 4-volt cells makes a 16-volt battery.

Low voltage system integrity is essential in an xEV. When the vehicle powers up (ready mode), the 12-volt system provides power to all modules, which control sensors and actuators. Safety-related modules, such as the high-voltage battery control module will perform safety checks before it permits high voltage to exit the high-voltage battery. If a vehicle's low-voltage battery is low on charge or dead, the vehicle will not power up and it will require a jump start to energize the system.

High-voltage battery



High voltage battery from a 2016 Nissan Leaf

Most xEVs utilize a high-voltage battery, but some smaller micro or mild hybrids use a battery of 48 volts or less. A medium, full hybrid, PHEV or EV battery might range from 144v (Honda Civic Hybrid) to as high as 924v (Lucid Air). The battery size, type, and chemistry help determine the vehicle's range, weight, charging speed, and cost.

Hybrid vehicles do not need a large battery because they are mainly storing energy recovered from vehicle deceleration. The battery has the task of storing regenerative braking energy, providing for powertrain control during stop/start driving, powering the low voltage electronics to a converter, and running the climate control system. On a hybrid vehicle, the engine will start and generate electricity as needed to keep the high-voltage battery at an ideal level. Most vehicles utilize a lithium-ion battery, but Toyota in particular still uses nickel metal hydride in some of their hybrid vehicles.

Plug-in hybrid vehicles use a larger battery than the standard hybrid vehicle to store enough energy to propel the vehicle in electric-only mode. After averaging common PHEV vehicles offered in 2024, electric-only mode of operation could achieve approximately 20 - 50 miles before resorting to engine operation, at which point the vehicle basically operates like a conventional hybrid.

As can be expected, a battery electric vehicle (BEV) uses a large battery. The battery is the only source of energy and it must contain a high enough capacity for the necessary range expected from the vehicle. This is where some manufacturers invest in energy-dense battery chemistries, higher voltage systems, and advanced thermal and battery management systems. The high-voltage battery is a large contributor to the cost and weight of the BEV. These attributes are also why there's constant advancement and innovation in battery technology.

Under the hood of a KIA EV 6, the box on top is the front motor inverter with battery power entering the right side, AC compressor power leaving the lower right, and PTC heater circuits leaving the left side.

High voltage inverter

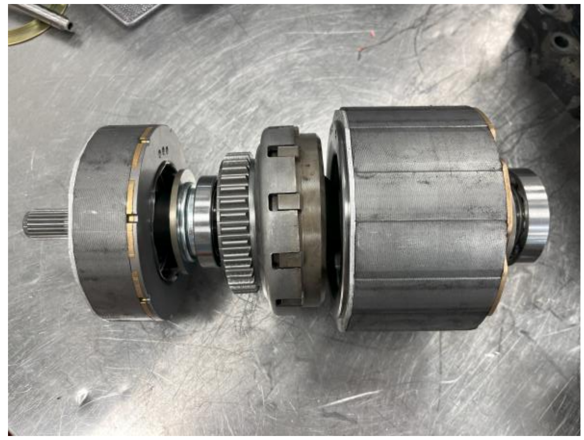
The high-voltage inverter converts alternating current into direct current and direct current into alternating current. An inverter is necessary because electrical energy can only be stored in a battery as direct current. Batteries store direct current with the basic concept that electron movement from the anode to the cathode does work, like driving an electric motor. And electron movement from the cathode to the anode recharges the battery.   Exposing a battery to alternating current would charge and discharge the battery continuously therefore not allowing for any energy storage.

Motor

With HEV and PHEV vehicles, the motor(s) coexist with an internal combustion engine. There are a variety of different motor designs, which we will explore in section five, but there are some common operational characteristics that exist among most xEV motors.

High voltage motor with the torque converter from a Ford F150 Hybrid

An EV motor contains two major parts - the rotor and the stator. There are other components within the motor assembly, such as position sensors, temp sensors, oil pumps, and gear reduction units, but when generically thinking of motor operation, the rotor and the stator are the main players.


Two rotors from a Toyota Hybrid Transaxle

The rotor is the "rotating" part of the motor and depending on the application, it might be connected to the engine or the driveline, or possibly both. For example, the Toyota Hybrid Synergy Drive (THS) uses two motors in its transaxle. One motor (MG1) connects to the ICE through a planetary gearset. The second motor (MG2) connects to the driveline, but it's also connected to the planetary gearset.

The stator is the "stationary" part of the motor and it is connected to the inverter and controlled via 3-phase current.

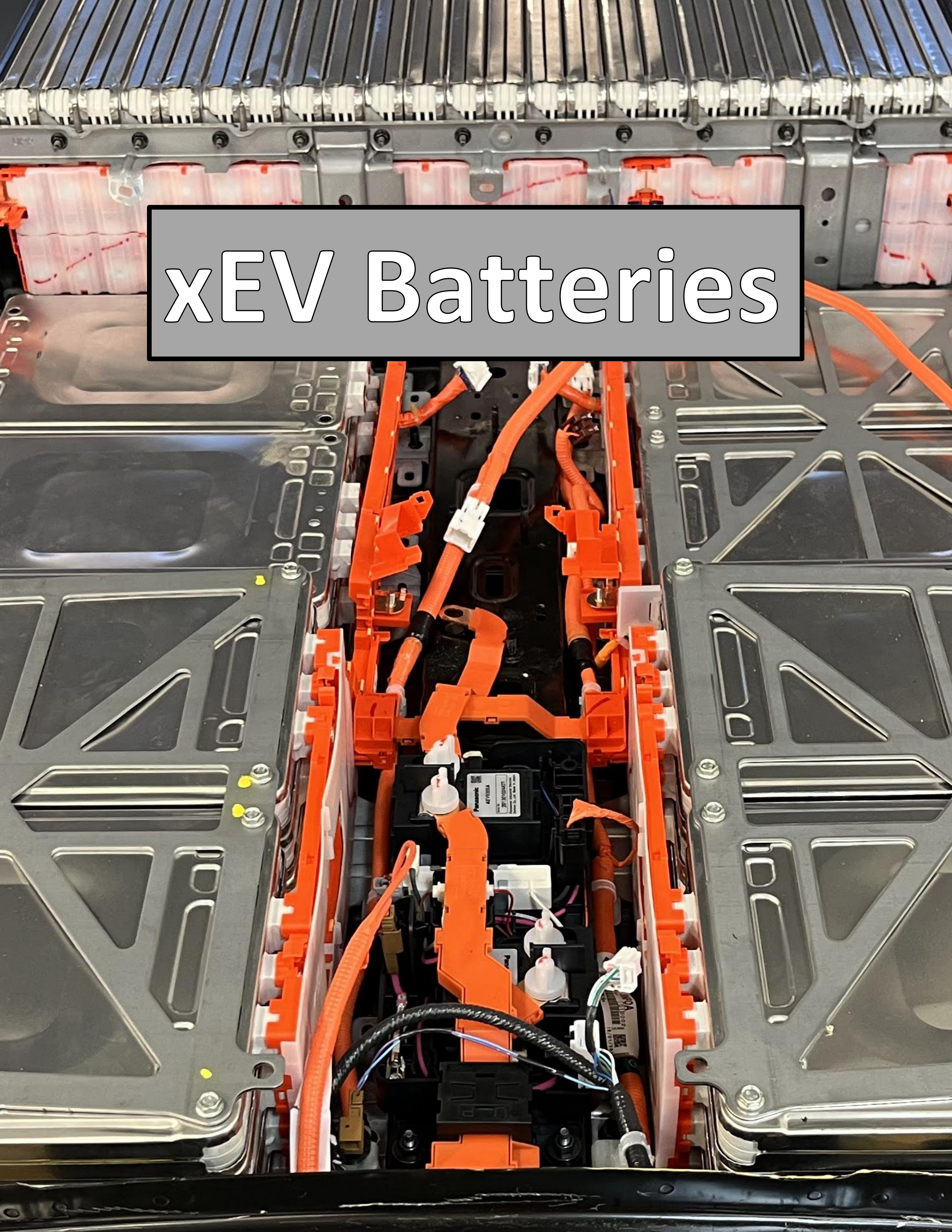
Charging

Level one charging

If the vehicle is a plug-in hybrid (PHEV) or a battery electric vehicle (BEV), there will be a charge port to allow for external power to charge the high-voltage battery. There are three levels of charging and several plug configurations. When considering battery charging, it's important to keep in mind that a battery is similar to a fuel tank in a gas vehicle. The battery is the fuel tank storing energy in chemical form instead of liquid form. The amount of time it takes to "fill" the battery depends on the size of the battery and the amount of current you can deliver to the battery. A larger battery will take a longer time to charge from 20% to 80%. A weaker charger will take more time because it cannot deliver energy as fast.

More details on charging is found in section seven.

xEV Batteries



3 - Battery Systems

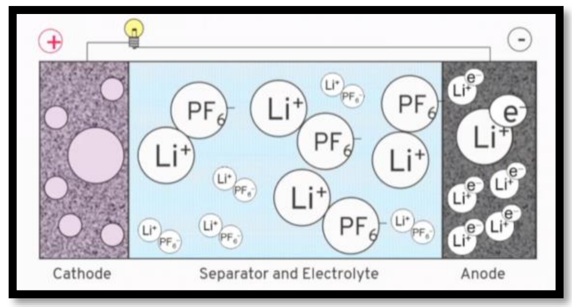
The purpose of the high-voltage battery is to convert chemical energy to electrical energy. Ultimately this powers the electric motor (mechanical energy). Batteries used for automotive powertrain applications are considered secondary batteries, which is simply another term for rechargeable batteries. The idea behind a secondary battery is that it can be repeatedly charged and discharged. Secondary batteries can be conventional lead-acid (PbA), nickel-metal hydride (NiMH), or lithium-ion (Li-ion).

Battery Terminology

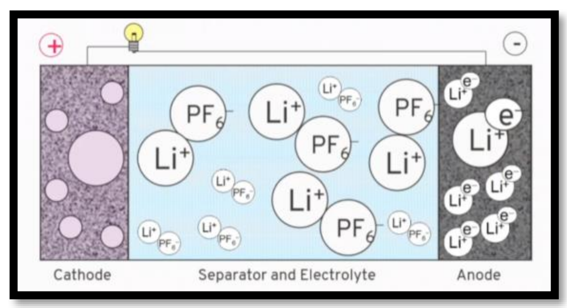
- Battery Cell: the basic battery unit is comprised of an anode, cathode, separator, and electrolyte
- Battery Pack: comprises multiple battery cells (or modules of cells)
- Battery cell quantity and arrangement within the pack effects
    - Energy storage
    - Pack voltage
    - Pack power

Cell Level Construction

Batteries consist of these main components – the anode, cathode, separator, and electrolyte.



Discharging



Charging

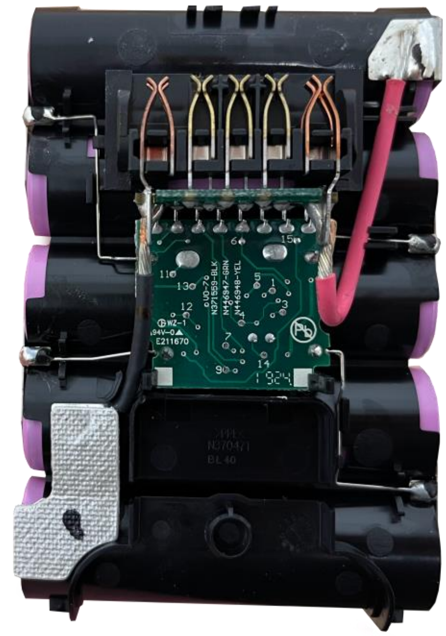
The anode is the negative plate in a battery cell. It commonly consists of Carbon (Graphite) or Silicon Alloys. When in a charged state, the crystal lattice structure of the anode stores lithium ions and their electrons. When discharging, the electrons travel from the anode, through the circuit, and end up at the cathode. The lithium ions travel from the anode via the electrolyte, through the separator, and join the electrons in the cathode.

The cathode is the positive plate in a battery cell. It commonly consists of various combinations of Lithium Metal Oxide, Iron Phosphate (FP), Manganese (Mn), Aluminum (Al), Nickel (Ni), and Cobalt (Co). The many different types of lithium batteries usually refer to the combination of these elements on the cathode. When discharging, the cathode receives and joins the electrons and lithium ions from the anode. During charging, the electrons flow from the cathode to the anode, and the lithium ions travel via the electrolyte to join the electrons back at the anode.

The electrolyte allows for ions to pass between the anode and cathode. It commonly consists of lithium salt.

The separator isolates the anode from the cathode. It allows for lithium ions to pass through, but not electrons. During discharge, the electrons will externally leave the battery cell and travel through the circuit from the anode to the cathode, and the lithium ions will travel via the electrolyte through the separator to join the electron at the cathode.

During charging, the opposite happens where the electron travels back to the anode through the circuit and the lithium ion travels through the electrolyte to join the electron back at the anode.

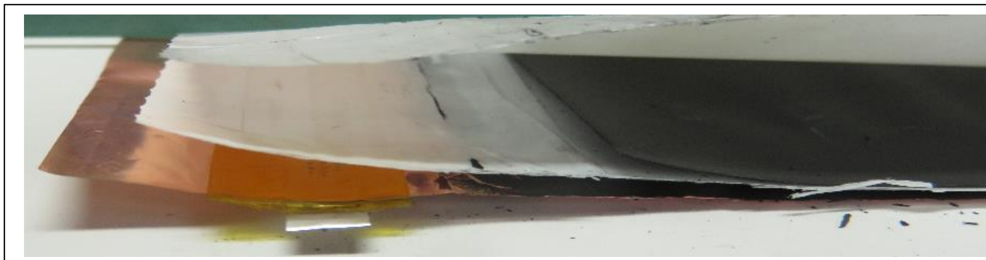


DeWalt pack

Battery Attributes

In the past couple of decades, a plethora of research has gone into the development of Li-Ion batteries. Research in the compositional makeup of the cathode and anode has improved the efficiency and power density of the battery greatly and it only continues to improve on a day-by-day basis. These battery chemistries can vary based on a few important characteristics, such as:

- Rated voltage
- Specific Power
- Specific Energy
- Energy Density
- Cycle live
- C-rate
- Thermal stability
- Safety
- Cost



Anode (copper) and Cathode (aluminum) from an 18650 cell (photo courtesy of Troy Wiemer)

The battery's “end of life” is typically determined by taking the beginning-of-life battery capacity and multiplying it by 80%. Some manufacturers will use 70% for warranty purposes, such as Tesla, Ford, Kia, and Hyundai. The goal would be to not drop below 80% of the beginning of life capacity in the vehicle’s usable lifetime.

Manufacturer warranties vary but expect at least an 8-year 100,000-mile warranty. In California, high voltage batteries are warranted for 10 years and 150K miles. Refer to the table for common manufacturers and their warranties.

Manufacturer	Standard Warranty	Percent degraded
Tesla	8 year, 150K (S and X), 120K (M3 LR, MY LR and Perf), 100K M3 and MY standard range)	70
Ford	8 years, 100K miles	70
Rivian	8 years, 175K miles	70
GM	8 years, 100K	60
Hyundai, Kia	10 years, 100K	70

Cost

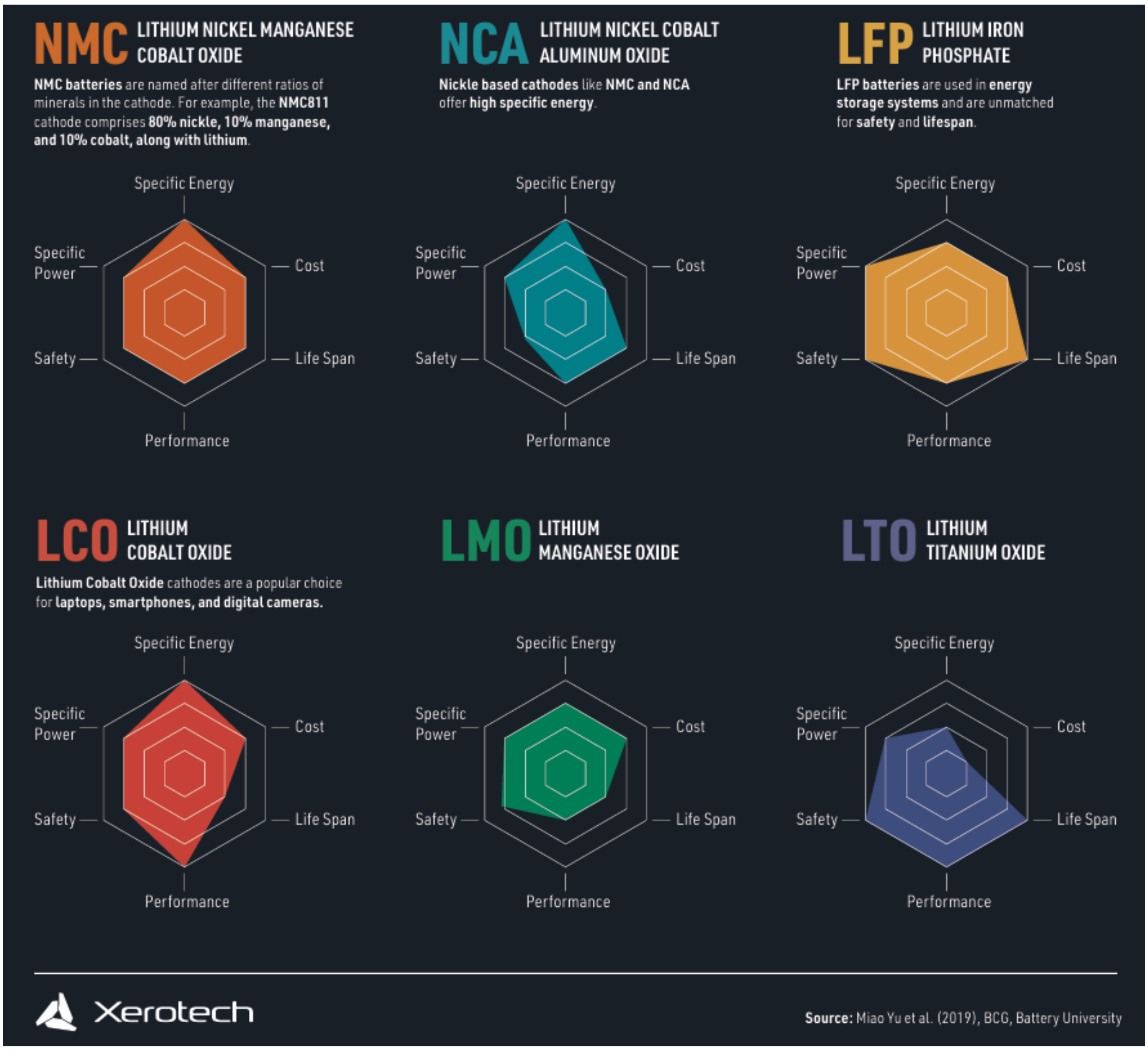
Battery cost is estimated to be approximately 40% of the total cost of vehicle production on average, although prices of battery packs are dropping year by year. In 2024, the average battery costs approximately $140 per kWh. This puts the price of a 75-kWh battery pack at $10,500. With consumers demanding vehicles with higher ranges, larger and more energy-dense batteries are becoming commonplace. These larger batteries weigh more, contain more precious elements, and cost more than smaller batteries. Improvements in battery technology and manufacturing are reducing the cost of the battery. Manufacturers are making efforts to reduce some of the more expensive elements in a battery with more cost-effective options. For example, shorter-range vehicles are often equipped with Lithium Manganese Iron Phosphate (LMFP) batteries that contain no Cobalt or Nickel, which are expensive elements.

For comparison's sake, here is a table with the part number and price of a vehicle's replacement battery supplied by repairlinkshop.com, which is a parts ordering system using dealer pricing and inventory.

3/23	Lightning	MachE	Bolt	ID.4	Leaf	EV6	Jeep 4xe
Model Year	22	22	22	22	20	22	23
Pack Size					62kWh		
Part Number	NL3Z10B759B NL3Z10B759A	NJ9Z10B759C NJ9Z10B759D	24052286	0Z1915910Q			
Pack Cost	38286.82 48243.91	33409.41 33667.06	15547.14	17,679.96			
Module PN	NL3Z10D672H	LJ9Z10D672BP LJ9Z10D672CB LJ9Z10D672AZ			295B95SF9D 295B95SF9C 295B95SF9E		
Module Cost	4316.07	4341.18 5967.06 4960.99			1913.91 903.41 1529.65		
Notes	Module cost was above list (4196.47)						

3/24	Lightning	MachE	Bolt	ID.4	Leaf	EV6	Jeep 4xe
Model Year	22	22	22	22	20	22	23
Pack Size						77.4kWh	
Pack PN	NL3Z10B759B NL3Z10B759A	NJ9Z10B759C NJ9Z10B759D	24052286	0Z1915910Q		37501CV051	68488244AA 5185101AH
Pack Cost	41,463.12 52,245.50	30837.65 31225.88	15547.14	11728.68		48,645.50	15,843.75 1,962.50
Module PN	NL3Z10D672H	LJ9Z10D672BP LJ9Z10D672CB	24294473 24282794		295B95SF9D 295B95SF9C		

		LJ9Z10D672AZ	24282799 24295446		295B95SF9E		
Module Cost	5,789.85	6,082.90 6,324.67 5,102.38	3,476.72 3,480.60 3,732.43 3,731.81		1913.91 903.41 1529.65		
Notes	Pack cost higher than list (37,246.78, 50797.76)	Module cost is higher than list (5,914.34, 6,149.41, 4,960.99)	GM has a listing for a high voltage battery, part number 19435899 for $624.00		Same price, no change		First PN is for HV pack, second is for 48V pack



Common Lithium Battery Chemistries

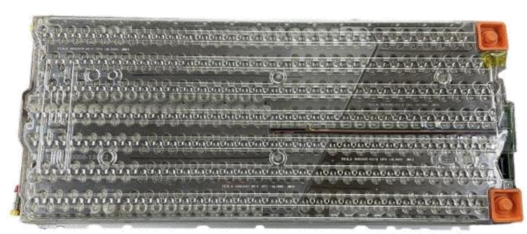
Form factor

Once the engineers decide on a chemistry to meet the vehicle's needs, the physical battery form is designed. There are three main configurations for battery cells, cylindrical, pouch, and prismatic. Each has its advantages and disadvantages. The form chosen plays a role in the battery cooling, power distribution (HV bus), battery height, and overall energy density of the battery pack.

Left to right – Aluminum billets representing the size of a 4680, 2170, and an 1865. An actual 1865 tab-less battery and a conventional AA battery is also in the lineup for comparison.

Cylindrical

A cylindrical lithium battery rolls up the anode, cathode, and separator plate in one can-shaped battery cell. The cells are identified by their size – width and length in millimeters. For example, an 1865 cell is 18mm wide and 65mm long. A 2170 cell is 21mm wide and 70mm long. A 4680 cell is 46mm wide and 80mm long. Those are the three common cylindrical cell sizes used in xEVs. See the picture to compare an AA battery to the three common cylindrical batteries.



Tesla Model S uses 16 modules with this 6s74p configuration

Advantages

- Structural – the battery is packed in a can that offers structural rigidity
- Stable cell size over time and temperature – very little swelling
- Ease of manufacturing
- Cell cooling options through the side of the can or through the end cap of the battery

Disadvantages

- Each battery requires packaging, which adds weight and takes volume
- Round cells do not make full use of the battery enclosure (wasted space around the battery)
- Smaller cells require large quantities, which require many welds for contacts

Pouch

The pouch-type battery contains the anode, cathode, separator plate, and electrolyte in a flexible envelope – or pouch. These battery cells have the highest energy density of all form factors since they make the best use of their packaging. Since the pouch is thin and flimsy, pouch cells typically require welding at the contacts and a dedicated housing to support the battery pouches. The pouch assembly also tends to swell over time and during hot operations, like heavy charging and discharging. The design of the battery pack requires provisions for this swelling, which may include foam or rubber products between cells. Many manufacturers use pouch-type cells, including General Motors, Ford Motor Company, Nissan, VW, and Hyundai/Kia. LG and SK are popular pouch cell manufacturers.

These pouch have tabs that are laser welded to connect to additional cells

Advantages:

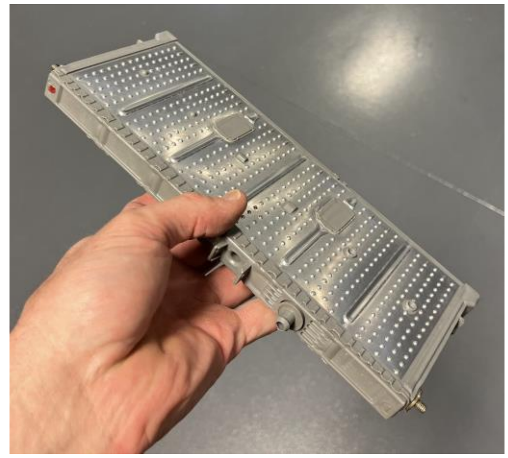
- Pouches can be made in various shapes and sizes
- Packaging is minimal, so the pouch cell offers great energy density
- Large pouches = high capacity, so fewer cells are needed. This can simplify manufacturing

Disadvantages:

- Pouches are non-structural, so they require structural housing
- Pouches swell over time and with high temperatures
- Contacts need to be welded, which can be strained by the movement of the pouch cells
- High-capacity cells also mean if one fails it can affect the overall capacity greatly

Prismatic

The prismatic cell is similar to the pouch-type cell, except the cells are layered and housed in a rigid container. Imagine the internals of a long pouch cell that is folded like a blanket and placed into a rigid housing. The prismatic cell has high capacity and often has the capability to bolt or fasten bus bars to transfer electricity from one cell to the next. It's also possible to enclose multiple cells into the same housing, as can be seen on the Toyota Prius with its NiHD battery shown. The prismatic form is most common with the LFP battery chemistry, which is found on lower-range vehicles. Auto manufacturers such as Tesla, VW, and BMW use prismatic cells. It might become a more popular cell format for economy EVs that have a lower, or standard, range option.



Prius battery uses a prismatic design.

Advantages:

- One container holds a lot of cell material
- Good packaging options
- Ease of construction

Disadvantages:

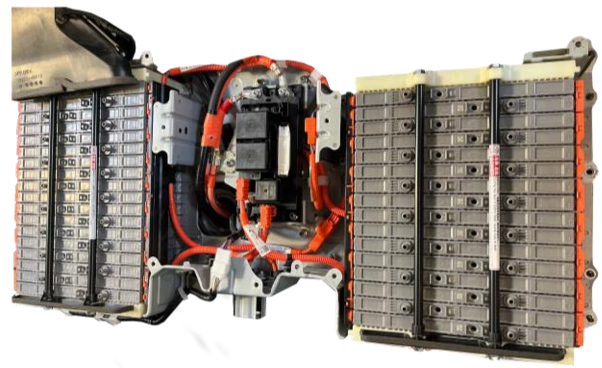
- Thermal control of the cell – uneven cooling

Future Advancements

- Solid State
- Silicon in anode
- Manganese in LFP
- PDO in Cathode
- Million-mile battery

Configurations

A battery cell by itself is only about 3.7 volts. That's good for a cell phone or a small electronic gadget, but an xEV needs hundreds of volts and the ability to deliver a lot of current at once. To achieve the necessary voltage, the battery cells are connected in series, and to meet the capacity and power demands, they might also be connected in parallel to multiple strings of batteries.



Toyota Rav4 NiMH battery with 34 modules made up of 204-1.2 volt cells for a nominal battery pack voltage of 244.8 volts

Hybrids commonly have single cells wired in series to achieve the necessary voltage. Since the hybrid's main function is to store energy generated during regen and output that energy during acceleration as well as some low-demand start/stop functions, a smaller battery is common.

A PHEV will need greater capacity since the vehicle's EV range is typically between 30 and 50 miles. Generally speaking, 30 to 50 miles in wattage equates to about 9600 to 16000 watts respectively, but the actual battery size is much larger since the battery management system wouldn't allow the battery to fully charge and fully discharge during this distance. The PHEV battery will likely have a series of cells to gain the necessary voltage, and then it would have parallel cells to add capacity.

Jeep 4xe PHEV battery (Photo courtesty of Joseph Ragnanese III)

A BEV, like the PHEV, needs even greater capacity, so there are likely more parallel cells to further increase pack-level capacity. A lot also depends on the battery's form factor. Pouch and Prismatic cells have a much higher capacity than cylindrical cells, so fewer parallel connections will need to be made.

Arrays/modules

In the simplest form, a battery would be a single pack made of up individual cells, wired in series, to achieve pack voltage. Many hybrid vehicles use this configuration because they don't require high capacity. In this simple example, the battery would consist of cells connected together to make a "battery pack." See the picture of the Toyota Prius battery pack as an example. In this Gen 4 Toyota Prius NiMH battery, 28 cells containing a nominal 7.2 volts are wired in series to create a 201.6-volt battery pack.

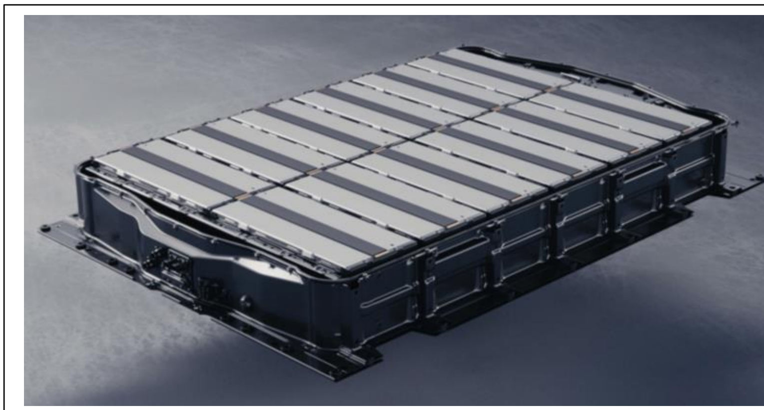
Gen 4 Prius NiMH Battery

If the manufacturer needs to add capacity, the battery assembly will be divided into smaller sections often referred to as modules or arrays. Within these modules, the battery might be divided into smaller units again called subpacks.

There is no standard and each manufacturer has their unique configuration and design. On the Hyundai EV shown in the picture, the engineers designed an 800-volt architecture by combining eight modules in series. Within each module, there are four sub-modules, each with six battery cells. Hyundai uses pouch-type cells, so each cell has a relatively high capacity.

Hyundai's Electric Global Module Platform – E-GMP

Some manufacturers may add parallel connections to increase battery pack capacity and ultimately vehicle range. Take for example the GMC Hummer/Silverado/Escalade IQ EV with the Ultium battery pack. GM refers to the battery module as the "cell module assembly." The complete battery pack contains 24 of these modules, but they are configured in two smaller packs within the complete assembly. Each module is nominally 33 volts. Wiring 12 of these in series will allow for a 396-volt battery pack. Since there are two of these smaller packs in each battery assembly, GM can connect



GM's Ultium Battery Pack for the Hummer EV. Two stacks of 12 modules. The stacks can be wired in parallel for 400v of operation or wired in series to benefit from 800v charging.

these two packs in series to take advantage of level 3 800-volt charging, or during normal operation, it connects the two packs in parallel for added range.

Battery Management Systems

At the forefront of xEV conversation is battery safety. Many news stories of lithium-ion battery fires have tarnished the reputation of xEVs and other products. A portion of the public simply won't consider an xEV because of the stigma surrounding battery fires. A trip to the past will recall the Samsung Note tablet and the "Hoverboard" ban on airplanes because of their potential fire risk or the numerous laptop battery recalls for overheating and catching fire. It seems that every EV that catches on fire makes the evening news, and that demonstrates the necessity for a control system that closely monitors the high-voltage battery during charging as well as driving. To ensure safety and to increase the lifespan of the battery pack, an xEV uses a battery management system (BMS) for essential battery and high-voltage functions.

While some manufacturers, such as Hyundai and KIA refer to this module as a BMS, many have assigned it a different name, such as a Battery Pack Control Module (Stellantis), Battery Energy Control Module (Ford and GM), and Battery Condition Monitor Module (Honda/Acura). The BMS might monitor and control cooling system functions. The BMS is also responsible for controlling the high-voltage contactors, which allow high voltage to leave the battery pack.

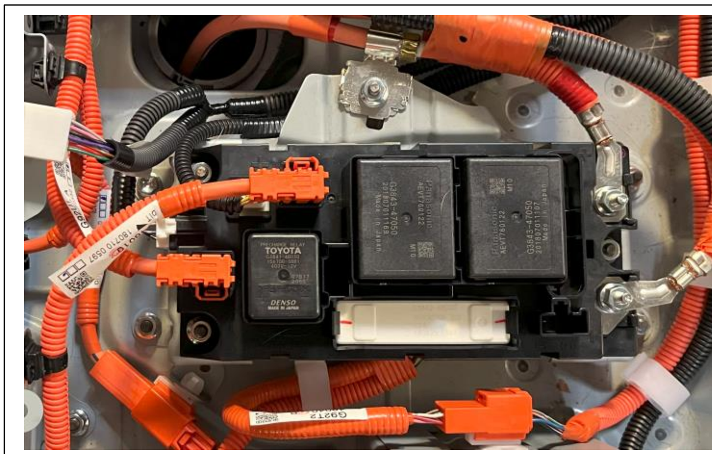
High Voltage Contactors:

As mentioned in section three, an xEV uses contactors to permit high voltage to leave the battery pack. For each contactor, the BMS controls an isolated low-voltage control circuit that energizes an electromagnet that closes the high-voltage contactor circuit. xEVs use at minimum a positive and negative contactor and a pre-charge contactor. A PHEV and BEV will also include high-voltage charging contactors and vehicles equipped with DC fast charging will include DC fast charge contactors.

Contactor Sequencing:

On this Toyota RAV 4, the pre-charge resistor is located on the negative side of the battery circuit. As can be seen in the scope image, the contactor sequencing is Positive Contactor ON first, Pre-charge Contactor on SECOND, and Negative Contactor ON last. The contactor sequence takes about 0.5 seconds.

During the shutdown, the negative contactor opens first.



Rav 4 Hybrid HV Contactor Assembly

Cooling:

The BMS is often in charge of battery thermal management by controlling coolant pumps and valves on liquid-cooled systems or controlling an air-circulation fan on air-cooled systems.

Liquid-cooled systems: The BMS monitors coolant temperature and adjusts electronically controlled valves to ensure the coolant temperature is ideal for the battery cells. When the battery cells are cold, the BMS controls the pump and valves to direct coolant through a heat exchanger. This warm coolant raises cell temperature to preferred levels. When the battery is running hot, the BMS controls the pump and valves to direct coolant through a chiller. This chilled coolant cools the cells to optimal levels. Ideal temperature levels are between 15 and 35 degrees C. By managing cell temperature, the thermal management system helps improve vehicle performance (warm batteries deliver current more efficiently), increases charge rate (either by cooling hot cells or warming cool cells), improves cell lifespan, and improves battery pack safety.

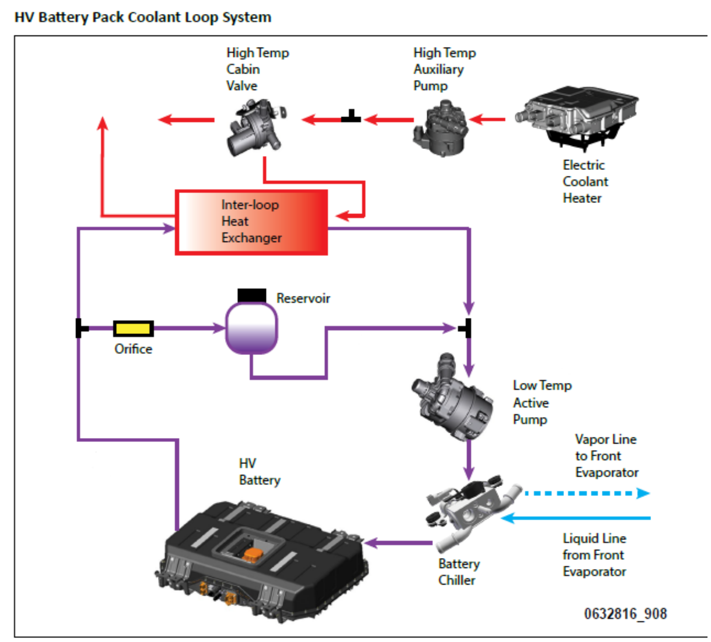


Figure 111 High-voltage Battery Pack Cooling System

Air-cooled systems: Most hybrid battery packs are air-cooled since they don't experience the demands of a BEV. The air-cooling system typically draws cabin air past the batteries and expels the air to the trunk or possibly outside. The battery fan motor is typically variable speed and the BMS changes motor speed based on battery temperature.

Balancing:

The BMS internally controls cell balancing functions. This feature is very important for the longevity of the battery pack. When cells become out-of-balance, charge and discharge efficiency is greatly affected. The battery can only safely discharge to its minimum voltage and it can only safely charge to its maximum voltage. Ensuring that all cell groups charge and discharge equally is essential to ensuring the maximum capacity of the battery pack.

Module Balancing:

Since many battery packs are comprised of multiple modules, replacement modules (or sub-modules) will need to be balanced to match the remaining pack modules. OE manufacturers require special tools to accommodate these service procedures. Hyundai/KIA and Ford uses the Midtronics xMB-9640 to charge/discharge the module to match a specific voltage.

Ford describes in their service information that the technician is to use a scan tool and retrieve battery health data. Within this battery health data, the technician can retrieve a generated voltage target code to enter into the balancer. This process needs to be performed for all modules being replaced and may take up to 6 hours per module.

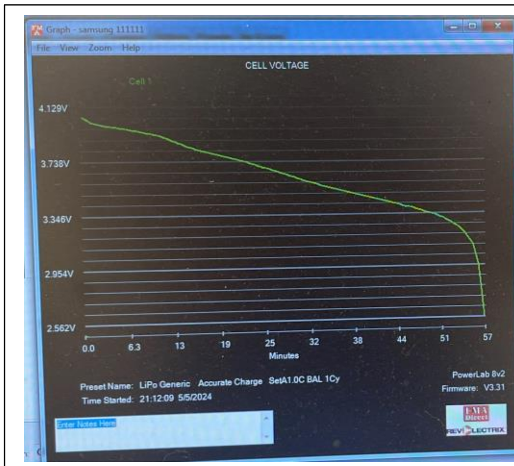
The Chevrolet Bolt battery module balancing procedure uses a Midtronics GRX-5100, which is a fully featured battery service tool. This tool uses various harnesses and attachments to communicate to the BMS for feedback regarding the module charging and target voltage. The tool is programmed with the vehicle details and all functions are controlled through the tool’s interface.

BMS Processes:

Battery State of Charge (SOC)

The battery SOC is the amount of charge remaining in the battery compared to the battery’s maximum capacity. Determining the battery’s SOC can be quite complicated.

System Voltage: One would think simply measuring battery voltage would be an effective method for determining the battery’s SOC. But, as can be seen in the plot from a common lithium-ion battery cell, the voltage drop is not linear and tends to fall off a cliff when the battery is nearly discharged. This method is not very accurate for determining SOC. The BEV displays the SOC as a percentage or range in miles, therefore the estimation must be accurate. It's important to remember that many factors influence the SOC, such as cell voltage level, current delivered/received, and temperature as well as battery age and number of cycles.



NCA discharge plot

Coulomb Counting uses the current sensor to closely monitor amperage entering and leaving the battery. This value, combined with cell voltage, temperature, and adjusted for age can provide the BMS with enough information to estimate the SOC.

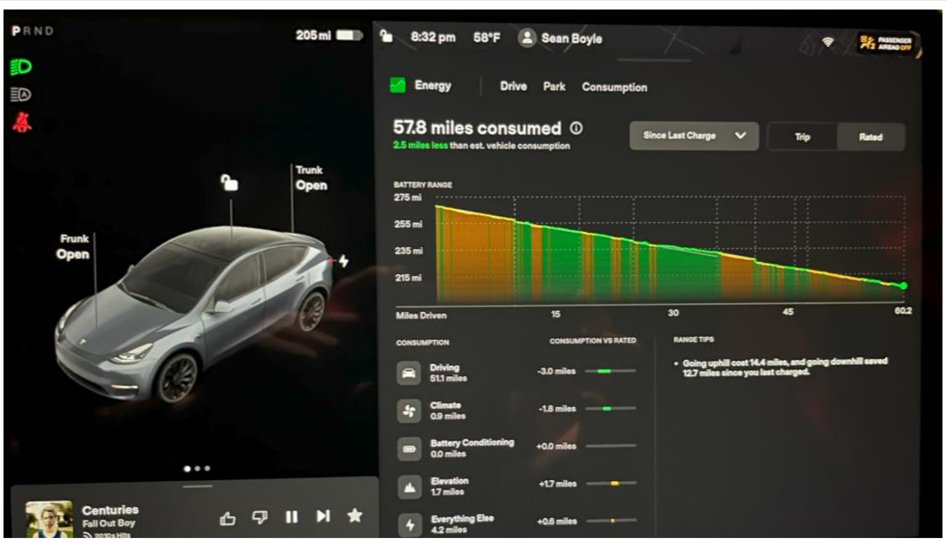
The battery SOC can be found through diagnostic scan data, such as the following screenshots depict:

Name	Value
Hybrid Battery Pack Voltage (V)	280.56
Hybrid Battery Current (A)	0.9
Hybrid Battery State Of Charge (%)	52.47
Leakage Resistance Overall (Ohms)	1638375
Active Diagnostic Session	1
Leakage Resistance Bus - (Ohms)	1638375
Average Temperature Range (°F)	46
Battery Age	50.37

Ford Fusion Hybrid

Name	Value
HV Battery Voltage (V)	380
HV Battery Current (A)	-32
HV Battery Level (W/h)	113280
HV Battery Level (%)	78
Battery Voltage (V)	12.96
12 Volt Battery Current Average (mA)	-126

Nissan Leaf



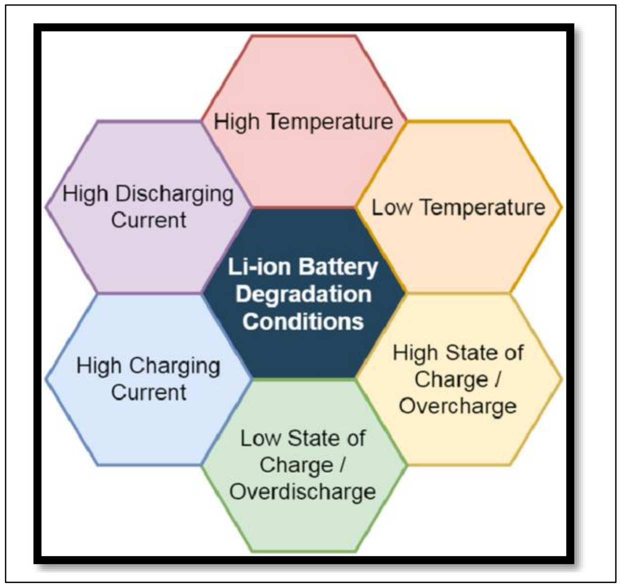
Tesla Model Y energy consumption after last charge event.

Battery State of Health (SOH)

The battery's SOH is an indication of how much it's degraded over time. The consumer can determine this by dividing the original range into the available range. For example, if originally the vehicle's battery offered 300 miles of range, and now after 5 years and 120K miles, the max range displayed is 280 miles, dividing 300 into 280 indicates that the battery is 93.3% of the original capacity. The SOH would be 93.3%. The algorithm considers the battery age, the amount of current the battery can accept and deliver, and the number of cycles.

The BEV might have a process to accurately check the battery's SOH. In the Tesla MY, in Service Mode, the SOH calculation can be commanded. It requires that the battery be below a certain SOC. The battery will fully discharge, then fully recharge, then fully discharge again. This process will show the most accurate battery SOH.

Degradation



Studies have found that battery degradation involves cell temperature, state of charge, depth of discharge, charge rate, discharge rate, and charge/discharge cycle total.

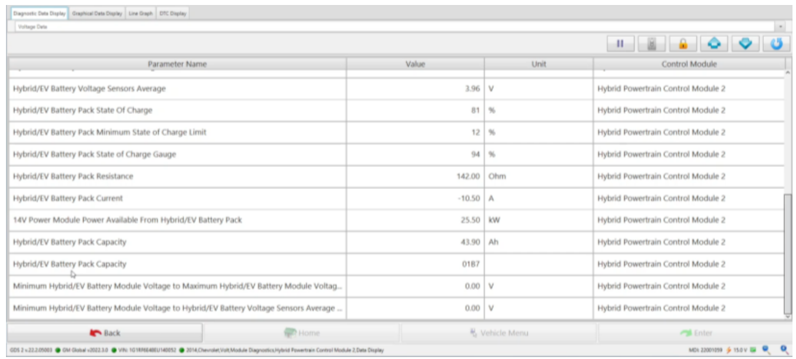
High Temperature: Keeping temperature in check will reduce battery degradation. Many thought that fast charging caused increased battery degradation, but it was found that fast charging wasn't as detrimental as initially thought if the battery cell temperatures were controlled.

Low temperature: Not as detrimental as high temperature, but a lithium-ion battery in low temperatures causes the battery components to shrink, which causes reduced ion movement in the electrode's intercalation gaps. As with high current charging, this can lead to lithium plating on the anode. Lithium deposits on the anode create a blanket effect where it impedes the movement of lithium ions into the intercalation gaps.

High current charging: Aside from the temperature increase, fast charging may lead to lithium plating, which limits fast charging capabilities as well as decreases battery life. During lithium plating, the lithium coats the graphite anode instead of entering the crystalline structure of the anode. This plating makes what could be called a secondary solid electrolyte interface (SEI), which acts to partially insulate the anode.

During fast charging, the lithium ions that would normally travel between the cathode and the anode could become consumed by "side reactions" and therefore do not contribute to the electrochemical energy transfer. These lost lithium ions can become part of the solid electrolyte interface (SEI), making it thicker. The loss of lithium ions reduces the cell's capacity.

Low SOC: The BMS will protect a lithium-ion battery from low voltage operation, but as discussed earlier, the lower the SOC, the greater the likelihood of the copper electrode dissolving and developing copper dendrites, which could cause a short circuit through the separator plate in the cell. Avoiding operating a BEV at low SOC levels will help alleviate the concern. HEV and PHEV vehicles will operate the ICE before allowing the battery to drop to low enough levels for this to be a concern.



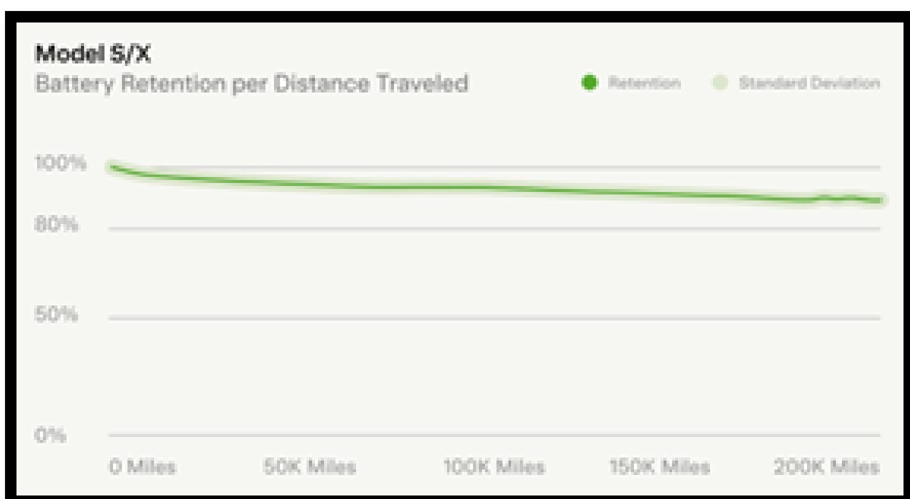
Parameter Name	Value	Unit	Control Module
Hybrid/EV Battery Voltage Sensors Average	3.96	V	Hybrid Powertrain Control Module 2
Hybrid/EV Battery Pack State Of Charge	81	%	Hybrid Powertrain Control Module 2
Hybrid/EV Battery Pack Minimum State of Charge Limit	12	%	Hybrid Powertrain Control Module 2
Hybrid/EV Battery Pack State of Charge Gauge	94	%	Hybrid Powertrain Control Module 2
Hybrid/EV Battery Pack Resistance	142.00	Ohm	Hybrid Powertrain Control Module 2
Hybrid/EV Battery Pack Current	-10.50	A	Hybrid Powertrain Control Module 2
14V Power Module Power Available From Hybrid/EV Battery Pack	25.50	kW	Hybrid Powertrain Control Module 2
Hybrid/EV Battery Pack Capacity	43.90	Ah	Hybrid Powertrain Control Module 2
Hybrid/EV Battery Pack Capacity	0187		Hybrid Powertrain Control Module 2
Minimum Hybrid/EV Battery Module Voltage to Maximum Hybrid/EV Battery Module Voltag...	0.00	V	Hybrid Powertrain Control Module 2
Minimum Hybrid/EV Battery Module Voltage to Hybrid/EV Battery Voltage Sensors Average ...	0.00	V	Hybrid Powertrain Control Module 2

Chevrolet Volt with a SOC battery and gauge value that's different.

High SOC: Like low SOC, the BMS will protect the HV battery from overcharging. Some manufacturers recommend against charging a battery to 100% because it not only takes longer to charge to 100%, but the potential stress on the battery is greater. A BMS that's not controlling the charge rate properly can cause battery failure or degradation because an overcharged battery can form lithium dendrites which can compromise the separator in the cell.

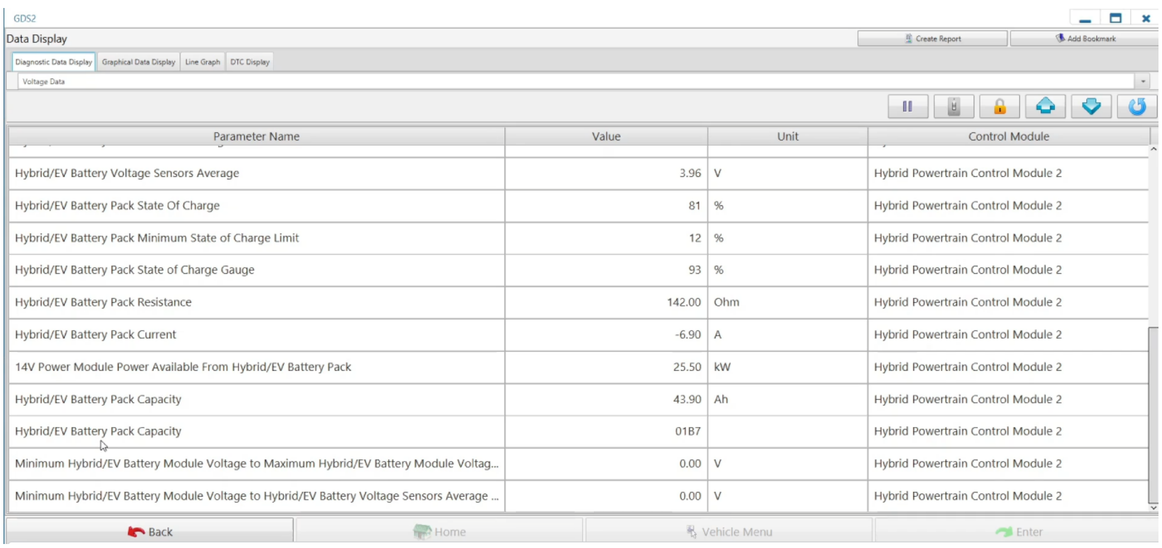
Most manufacturers recommend charging to 80% unless planning a long trip. An HEV and usually a PHEV will indicate 100% on a gauge even if the battery isn't fully charged.

Battery Degradation Data: Tesla has the greatest sample size of all EV manufacturers because of the total number of registered vehicles on the road. In 2023, Tesla reported degradation data for the Model S and X. Most batteries with 200K miles still had over 80% capacity. Similar data was reported on the Model 3 and Y showing strong capacity retention of less than 10% after 100,000 miles and less than 15% after 200,000 miles. Aside from Tesla, most EV manufacturers don't have significant numbers of EVs with enough miles to reliably calculate battery degradation.



Hybrid Battery Block 1 Voltage (V)	16
Hybrid Battery Block 2 Voltage (V)	16
Hybrid Battery Block 3 Voltage (V)	32
Hybrid Battery Block 4 Voltage (V)	32.05
Hybrid Battery Block 5 Voltage (V)	31.95
Hybrid Battery Block 6 Voltage (V)	32
Hybrid Battery Block 7 Voltage (V)	32
Hybrid Battery Block 8 Voltage (V)	15.97
Hybrid Battery Block 9 Voltage (V)	16
Internal Resistance 1 (Ohms)	0.019
Internal Resistance 2 (Ohms)	0.019
Internal Resistance 3 (Ohms)	0.019
Internal Resistance 4 (Ohms)	0.019
Internal Resistance 5 (Ohms)	0.019
Internal Resistance 6 (Ohms)	0.019
Internal Resistance 7 (Ohms)	0.019
Internal Resistance 8 (Ohms)	0.019
Internal Resistance 9 (Ohms)	0.019

2016 Toyota Prius Battery Data



Parameter Name	Value	Unit	Control Module
Hybrid/EV Battery Voltage Sensors Average	3.96	V	Hybrid Powertrain Control Module 2
Hybrid/EV Battery Pack State Of Charge	81	%	Hybrid Powertrain Control Module 2
Hybrid/EV Battery Pack Minimum State of Charge Limit	12	%	Hybrid Powertrain Control Module 2
Hybrid/EV Battery Pack State of Charge Gauge	93	%	Hybrid Powertrain Control Module 2
Hybrid/EV Battery Pack Resistance	142.00	Ohm	Hybrid Powertrain Control Module 2
Hybrid/EV Battery Pack Current	-6.90	A	Hybrid Powertrain Control Module 2
14V Power Module Power Available From Hybrid/EV Battery Pack	25.50	kW	Hybrid Powertrain Control Module 2
Hybrid/EV Battery Pack Capacity	43.90	Ah	Hybrid Powertrain Control Module 2
Hybrid/EV Battery Pack Capacity	01B7		Hybrid Powertrain Control Module 2
Minimum Hybrid/EV Battery Module Voltage to Maximum Hybrid/EV Battery Module Voltag...	0.00	V	Hybrid Powertrain Control Module 2
Minimum Hybrid/EV Battery Module Voltage to Hybrid/EV Battery Voltage Sensors Average ...	0.00	V	Hybrid Powertrain Control Module 2

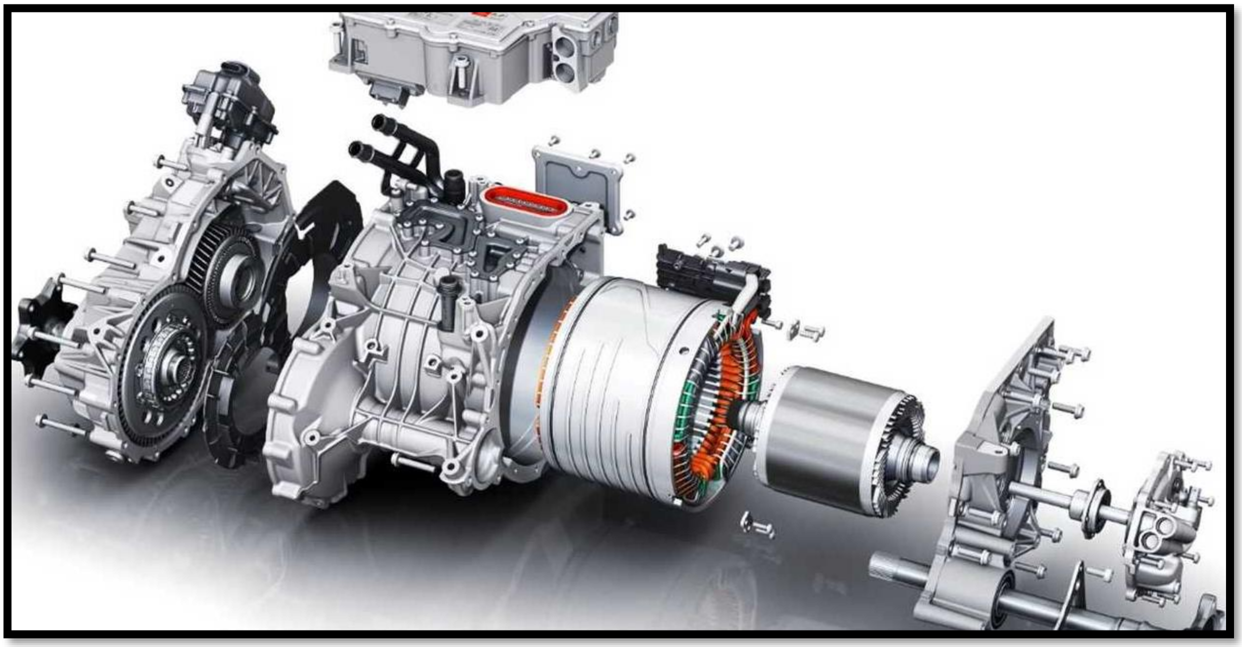
Chevrolet Volt Battery Data

Extra resources:

- Designing a Battery Pack ? - Battery Design
- Battery Pack | Tech Talks | Lucid Motors (youtube.com)
- Electric Vehicle Battery Breakdown: Cells to Modules to Packs! (youtube.com)

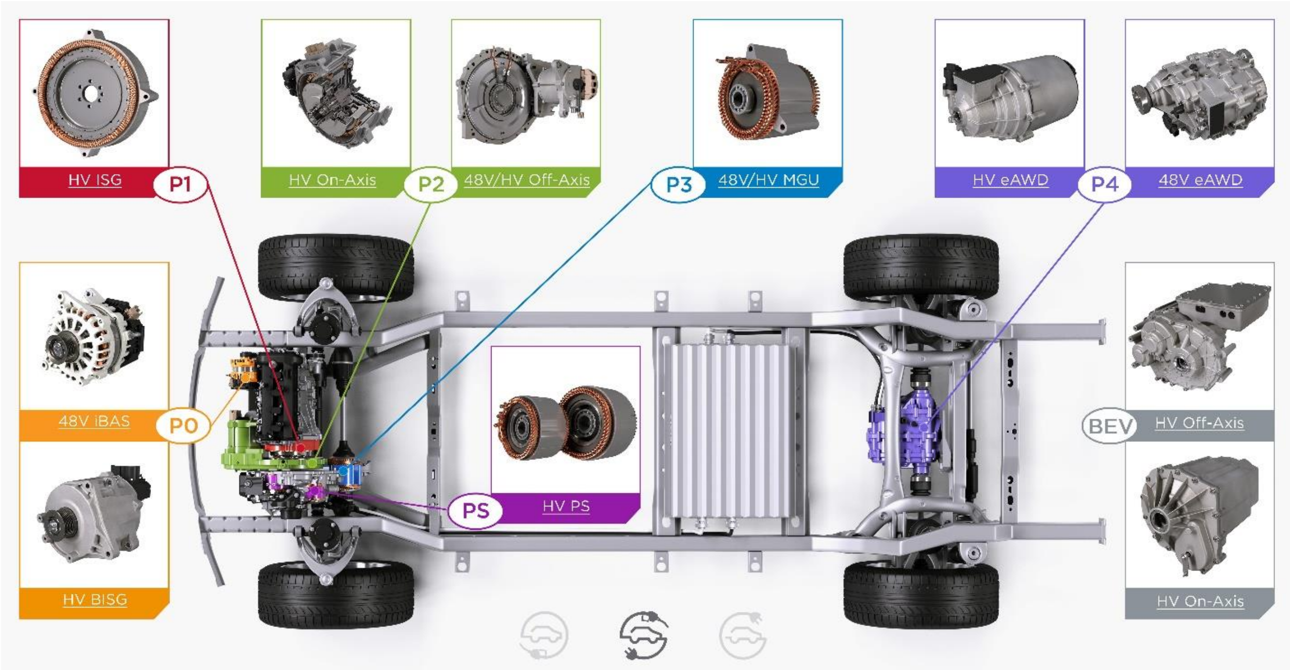
xEV Motors

4 – Electric Motors



The electric motor is the muscle for the xEV. It's the component doing the work by delivering torque to the driveline. Electric motors use magnetic interaction between components to convert electrical energy into mechanical energy. In an xEV, work is performed by the electric motor, whether independently or in conjunction with the internal combustion engine. The motor replaces an internal combustion engine on a battery electric vehicle (BEV) and it works to assist the internal combustion engine in a hybrid electric vehicle (HEV). The motor is often referred to as a "machine" because it can propel a vehicle or generate electricity. An electric machine generates electromagnetic forces that can be used to move a vehicle or generate electrical power and it's commonly rated in kW which can be converted to HP by dividing the kW rating by 746.

Motor Designations



Motor locations diagram from Borg Warner

Because of the vast motor applications for an xEV, some service training information refers to a motor designation system when describing the attributes of the motor.

P0 motors are also known as Belt – Alternator – Starter motors. They are located on the front of the engine and assist the engine in torque production, charge the HV battery during regen, and allow for engine starting functions. The P0 motor might work in conjunction with other motors in the vehicle. The eTorque system on the Jeep or Ram truck is a good example of the P0 motor.

Ram eTorque – P0 location

P1 motor is a parallel design located between the engine and the transmission. The P1 serves to assist engine torque during acceleration, operate as a generator during deceleration, and allow for engine starting. The P1 motor's rotor is connected to the engine flywheel. The Honda Insight or Civic Hybrid is a good example of a P1 motor.

The P2 motor is similar to the P1 motor, but it's located after a mechanical coupling that allows the engine and transmission to be separated. This is necessary for a vehicle to work in motoring mode while the engine is not rotating. The Ford F150 Hybrid is an example of a P2 motor.

A PS motor is actually a combination of two motors connected to a power-split device (planetary gearset). The PS is a common HEV/PHEV design that Toyota pioneered in the late 90's for use on the Toyota Prius. Variations aside, the PS motor is used by many manufacturers, such as Ford, Toyota, GM, Honda, and Stellantis.

Power split (PS) between MG 1 and MG2 from a Toyota Prius

A P3 motor is found after the transmission and before the final drive. Although not as common, the Subaru Crosstrek Hybrid uses a motor in the P4 configuration.

The P4 motor is most common with all-wheel drive (AWD) applications. The P4 is located at the drive axles and propels the wheels either directly or through a gear reduction unit. P4 motors are common on Toyota AWD products, such as the Rav4 and Lexus RX300h.

Lastly, the BEV motor also drives the wheels through a gear reduction unit.

Basic Motor Components

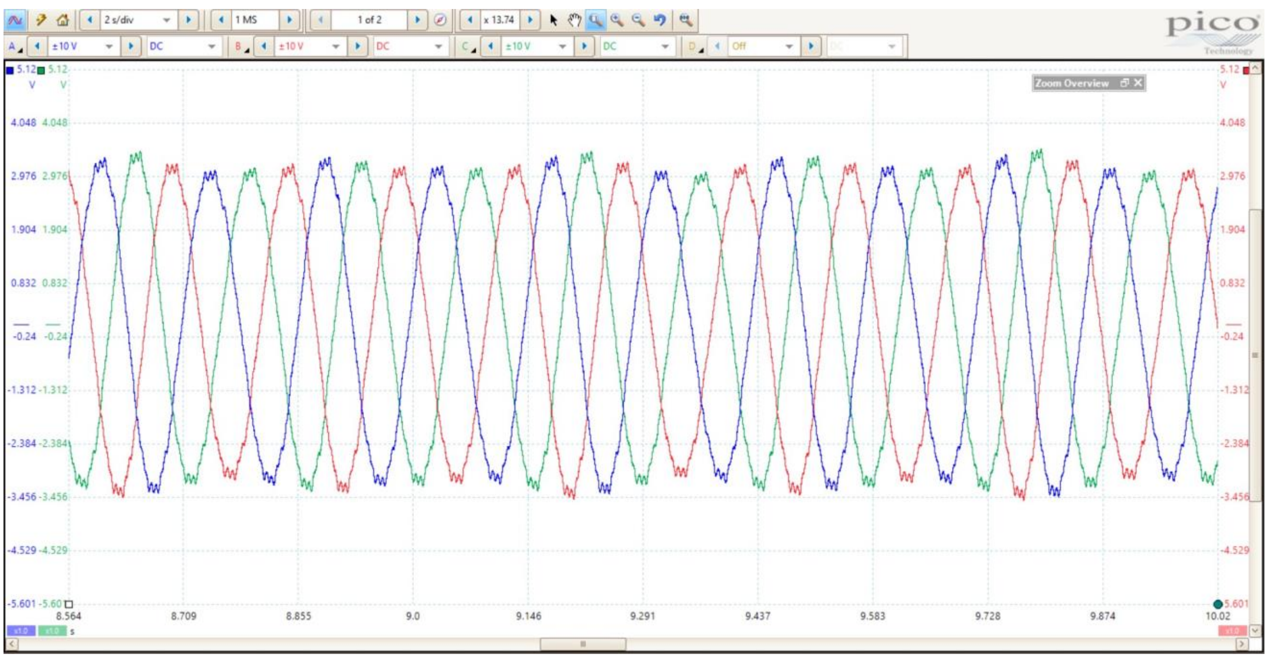
Broken down into its simplest components, an electric motor contains a stator and a rotor. The stator is the stationary component that is comprised of a series of coils that generate an electromagnetic field. In most automotive applications, it contains a series of windings that are evenly spaced around the circumference of the rotor. An inverter (section six) controls electrical current through the stator windings, which generate a rotating magnetic field (RMF). This RMF interacts with the motor's rotor, which is the rotating component of an electric motor. The xEV motor uses three electrical circuits in the stator, called phases, to drive the rotor.

On a BEV, the rotor is connected to the drive wheels through the use of a gear reduction unit. On an HEV, the rotor could take on various functions based on how the motor is used and the location of the motor. For example, the rotor may simply be used to assist the engine through a belt drive as found on some mild hybrids (Stellantis E-torque). If the electric motor is sandwiched between the engine and transmission, the rotor might drive the input to the transmission (Ford F150 Hybrid). The vehicle could employ two electric motors within a transaxle with one that drives the wheels and the other that works with the engine and drivetrain to generate electricity while also applying driving force to the drivetrain (Ford and Toyota hybrid design).

Depending on the design, the rotor might use magnets or conductors and ultimately defines the type of motor, such as a **Permanent Magnet Synchronous Motor (PMSM) and Induction Motor (IM**). Regardless of rotor design, the electromagnetic field of the stator interacts with the magnetic field of the rotor to generate output torque. The following describes the stator function, design, and operation.

Phases

In an xEV, the AC voltage is delivered to the motor in three "phases" from the inverter assembly. The alternating current for each of these phases is shifted 120 degrees. Motor connections are often labeled X, Y, Z, or U, V, W, or even 1, 2, 3. Larger motors often use more phases such as the nine-phase electric motor used by Cummins in their medium-duty and heavy-duty applications. The three phases are connected in a wye configuration, where all three phases are connected together to form a "Y" shape. This configuration ensures that current will flow between each phase as the inverter controls the power and ground connections for each phase. This action will be described in more detail in section six – invertors.



Three phase AC Voltage generated by spinning a Nissan Leaf PMSM by hand. The 3-phases are spaced 120 degrees apart

The three-phase configuration allows the rotating magnetic field (RMF) to be smooth as it travels around the stator. As the AC voltage cycles through the three phases, separated electrically by 120 degrees, the electromagnetic field cycles smoothly between the north and south poles at whatever frequency the inverter commands. To further control magnetic flux transition, the stator will employ either a concentrated or distributed winding arrangement.

Concentrated windings around a PMSM

Motor Types

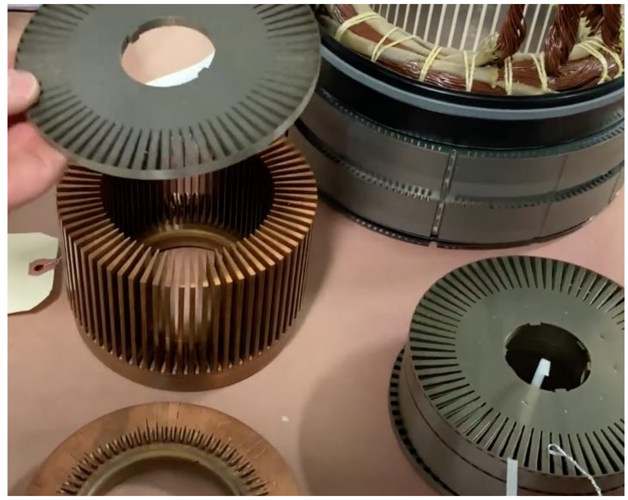
In an xEV, the motor type is defined by the rotor construction. Most vehicles use a permanent magnet synchronous motor (PMSM) or an asynchronous induction motor (IM). The term synchronous means that the rotor and stator's rotating magnetic field (RMF) are matched or synchronized, which is necessary on permanent magnet-type rotors. The term asynchronous means that the RMF is not matching or synchronized, which is necessary to produce torque with IMs.

Synchronous Internal Permanent Magnet (IPM) (PMSM)

A synchronous motor indicates that the rotating magnetic field (RMF) and the rotor need to be synchronized and revolving at the same speed. As mentioned, this feature is characteristic of an interior (internal) permanent magnet (IPM) motor.   Synchronous speed is necessary because if the motor falls out of synchronization, the RMF and permanent magnets will lose attraction and no torque will output. For this reason, the RMF needs to be precisely aligned with the rotor's magnetic fields. This system uses precise phase control through a motor controller and precise rotor position monitoring through the use of a resolver.

Asynchronous Induction Motor

In an asynchronous motor, the rotor and RMF do not need to revolve at the same speed. In fact, for torque to be produced, the RMF must be revolving faster than the rotor. This feature is a characteristic of an induction motor (IM).



Tesla induction motor with shorting bars connecting to end plates. Photo from Munro Live

Although not as popular as IPM motors, the induction motor is still commonly used in conjunction with IPM motors, but mostly as a front-drive on AWD applications. The Audi E-tron, Mecedes EQE, VW, and the Tesla S, X, 3, Y, and Cybertruck use the induction motor.

Rotor Design

The rotor does not include permanent magnets. It uses the voltage induced from the stator's RMF into the rotor's "shorting bars" to generate a magnetic field within the rotor. This generated magnetic field interacts with the stator's RMF.

Motor-related Service

Mach E motor, 1 – serial number, 2 – service number, 3 – part number

With most manufacturers, there are limited service opportunities related to the electric motor. Failures often result in the replacement of the motor assembly. When replacing a motor assembly, there will likely be calibration or sensor learning. For example, on the Ford Mustang MachE, the service information states that if the transmission (motor control) "strategy is not correct, transmission drivability WILL occur." This is due to the precise relationship that must exist between motor controller current and the position of the PMSM's rotor's magnets. When replacing the resolver or motor assembly, follow the service information to calibrate the resolver. In the case of the MachE, the service information has the technician use a scan tool and select "electric motor resolver offset programming" and add the serial number and service code from the motor.

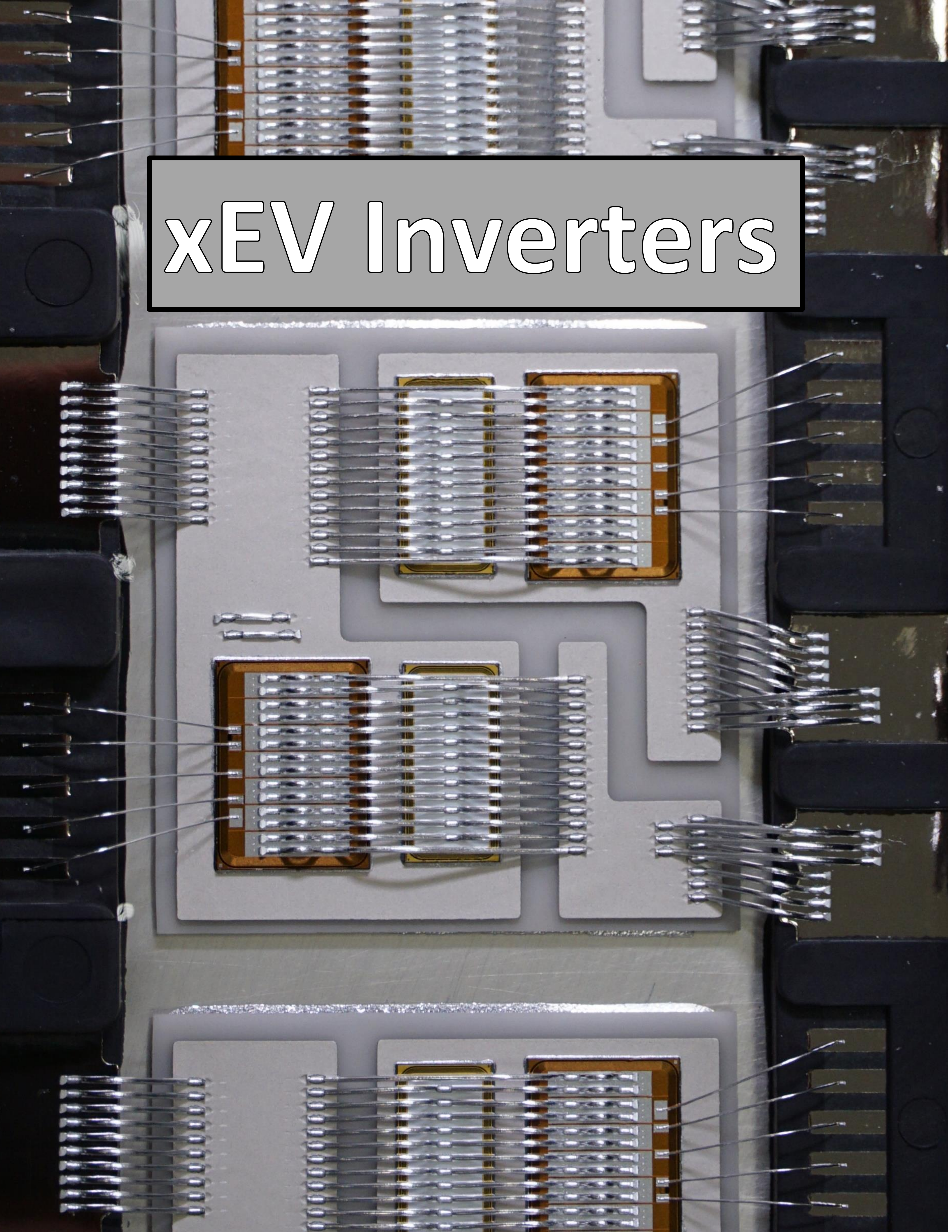
Additional resources

How alternating current motors work? (youtube.com)

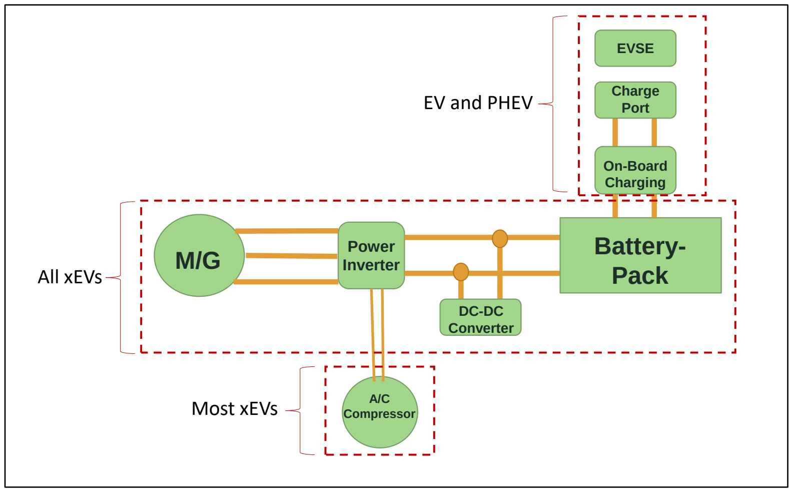
Synchronous motor with permanent magnets. (youtube.com)

Understanding RMF | The driving force behind every AC machine (youtube.com)

Understanding electric motor Windings! (youtube.com)

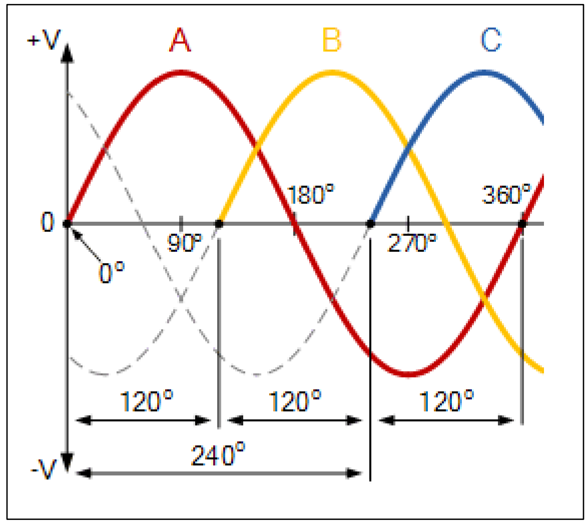

xEV Inverters

5 - Inverter Systems



The Power Inverter is the component that **converts HV DC from the battery pack to HV AC to drive the electric motor**. It is also responsible for **rectifying HV AC generated during regeneration to HV DC to charge the battery**. To perform this conversion, the inverter uses high frequency switching through Insulated Gate Bipolar Transistors (IGBT) or Silicon Carbide Metal Oxide Semiconductor Field Effect Transistors (SIC MOSFET).

Three Phase Operation

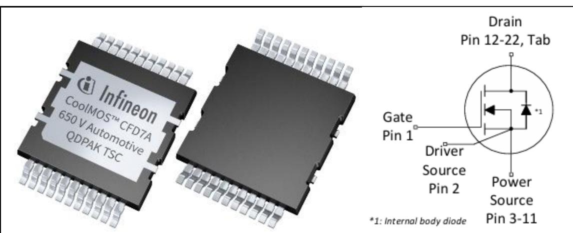


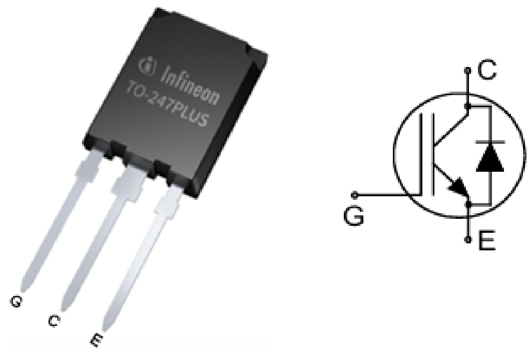
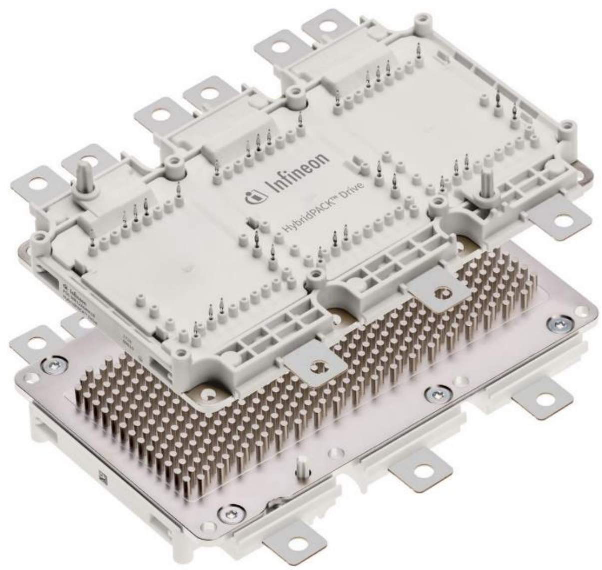
For three-phase (as opposed to single-phase) operation, typical power inverters for xEV use utilize six transistors (or transistor groups). . The goal of the inverter is to create three sinusoidal waves separated electrically 120° apart from one another. This will create a smooth and efficient rotating magnetic field (RMF) in the electric motor's stator.

Advances in transistor technology have made high frequency, high voltage, and high current power control a reality. The common transistors used in automotive applications include:

Transistor control

The advent of the xEV has as much to do with modern high-tech transistor control as it does battery technology. Advancements in transistors have allowed for highly efficient high current operation of the electric motor.

Common Metal Oxide Semiconductor Field-Effect Transistors (MOSFET) – These transistors handle high amperage and have high switching rates, but they are limited in voltage capacity. They are commonly used in audio amplifiers because they can simulate high-frequency audio signals and output high amperage to speakers. Their downfall regarding xEV motor usage is their voltage limitation.	 IPDQ65R017CFD7A - Infineon Technologies

Insulated Gate Bipolar Transistors (IGBT) – This transistor can handle high amperage, high voltage, and high switching rates. The advent of this transistor has allowed the xEV inverter to effectively control the high amperage of an xEV motor. IGBTs are also commonly used in high-voltage power inverters for electric grid and solar applications. It's a common transistor used in high-frequency inverter-type welding machines. The IGBT allows for the adjustable high-frequency AC waveform that allows welders to optimize their weld.	 [Automotive IGBT discretes - Infineon Technologies]()
Silicon Carbide Metal Oxide Semiconductor Field-Effect Transistor (SIC MOSFET) – This transistor takes the benefits of the IGBT and improves upon them. The SIC MOSFET handles higher switching rates and higher voltages and can handle higher heat than IGBT, which makes them ideal for 800+ volt systems.	 EV traction inverter | Automotive-qualified and highly efficient solution supporting a scalable range of motors and power classes - Infineon Technologies

Inverter layouts

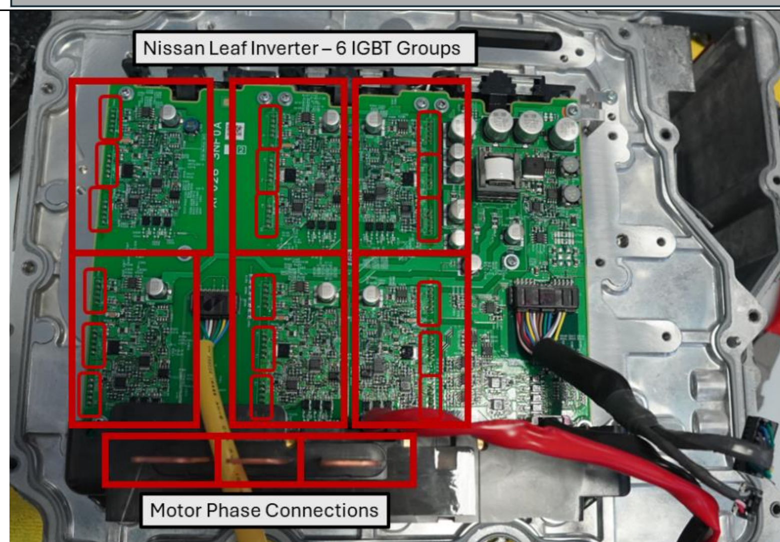
It's common to find inverters combined with other high-voltage components, such as the DC-DC converter and charge controller. These power inverter modules are layered with each section devoted to a specific function. On the Nissan Leaf inverter assembly, the charge controller functions and DC-DC conversion components are located under the lid

2013 Nissan Leaf

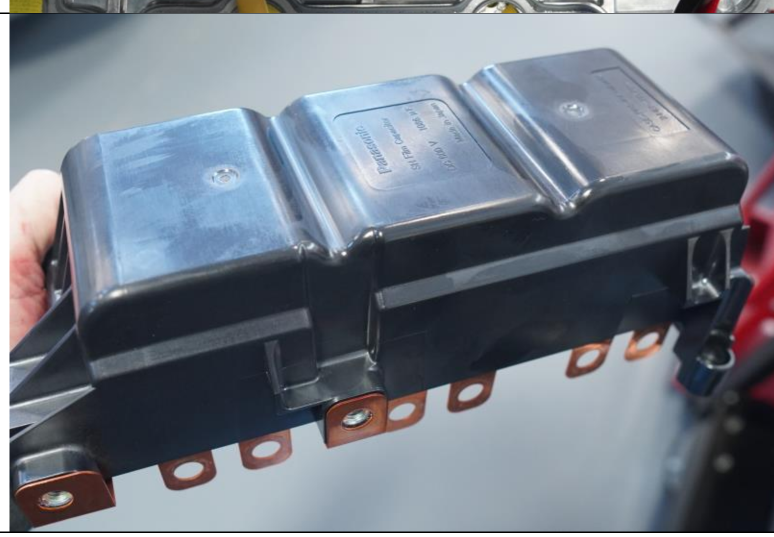
The componentry for the DC-to-DC converter and the onboard charger are accessible after removing the lid and some plastic shrouding.

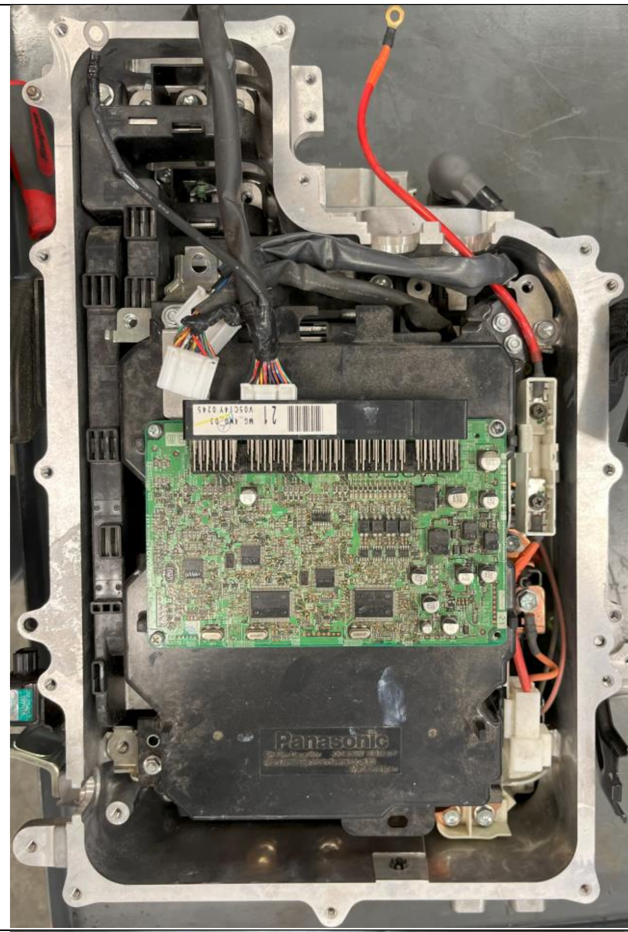
There is a liquid cooling plate under the circuitry.

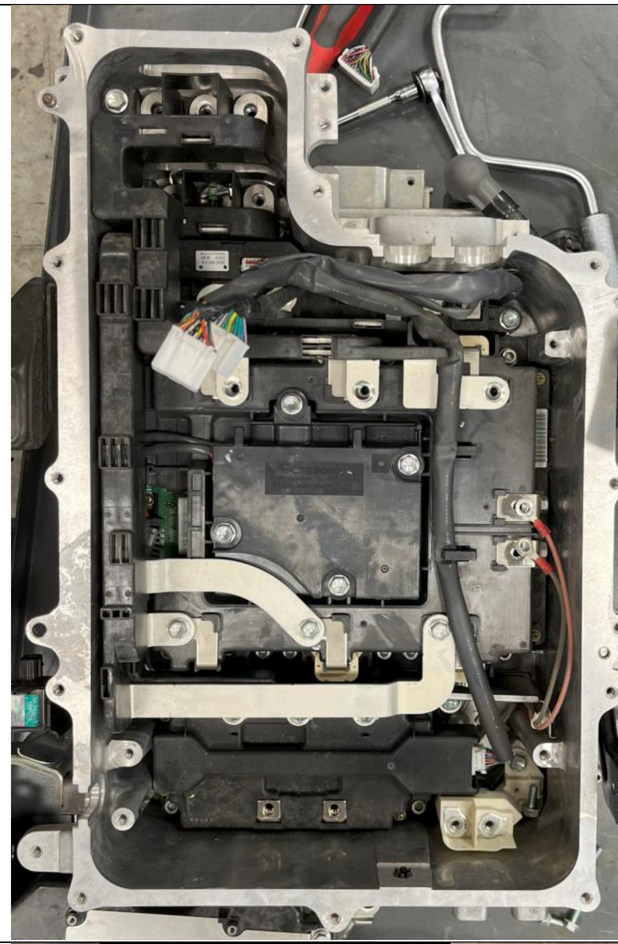
The Leaf inverter has 6 IGBT groups with three IGBT transistors per group. These IGBTs are attached to the cooling plate with thermal grease. In the image, the gate controller is visible with the solder connections for each IGBT. The motor phase connections are located at the bottom of the image.



DC power is supplied by a bank of capacitors and it's connected to the opposite side of the IGBT board in relation to the 3-phase connection. The capacitor is rated at 600v and 1086 microfarad.



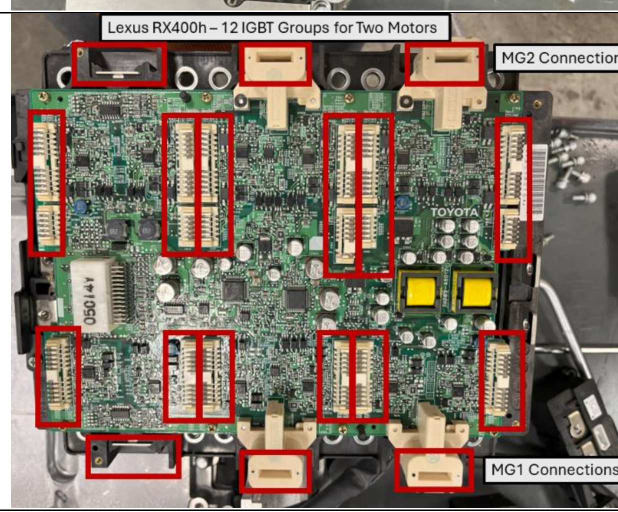
Lexus RX400h	
After removing the lid from the Lexus inverter assembly, the motor control module and the DC Link are visible. This inverter controls three motors, MG1 (primarily a generator and an engine starter motor), MG2 (drives front wheels), and the AWD motor. In the image, bus bars are visible transferring HV battery power to the DC link and the 3-phase power between the IGBTs and the motor connections.	
The Lexus Inverter has three DC links. The large capacitor bank is located under the motor controller and on top of the IGBT power module. These capacitors measured out to 2922 microfarads.	



The IGBT board shows how MG1 and MG2 are controlled. The top half of the image shows MG2, which is a higher KW motor, is controlled by six groups of three IGBTs.

The bottom half of the board shows six groups of two IGBTs that control MG1. The three phase connections for each motor are at the top and the bottom of the image. Notice that only two phases have amperage sensors.

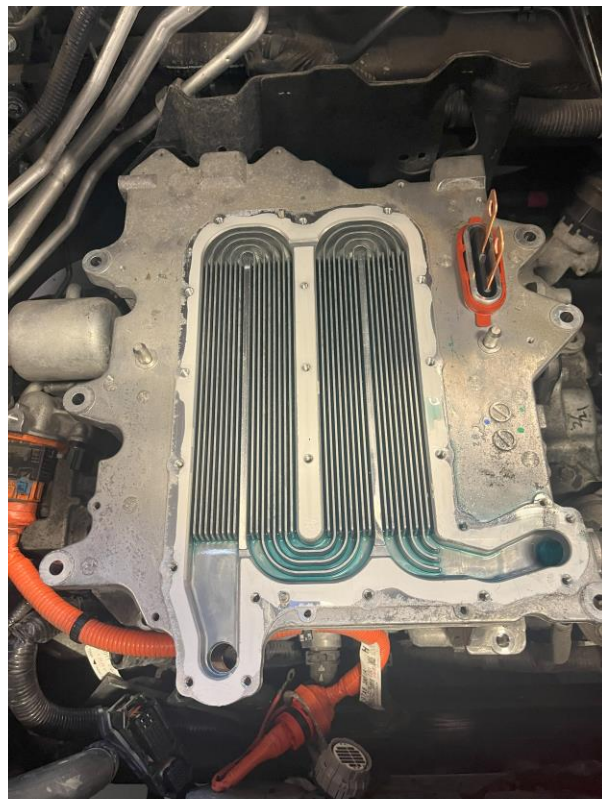
The DC power enters the transistors at the two-lug connection at the right of the board.



The smaller rear motor for AWD has its own inverter assembly with six single IGBTs, so no parallel groupings. Like the MG1 and MG2 transistors, the rear motor's IGBTs are coated in silicone. The three-phase connection is at the bottom of the IGBT board and the DC power in is at the top.	

Inverter Cooling

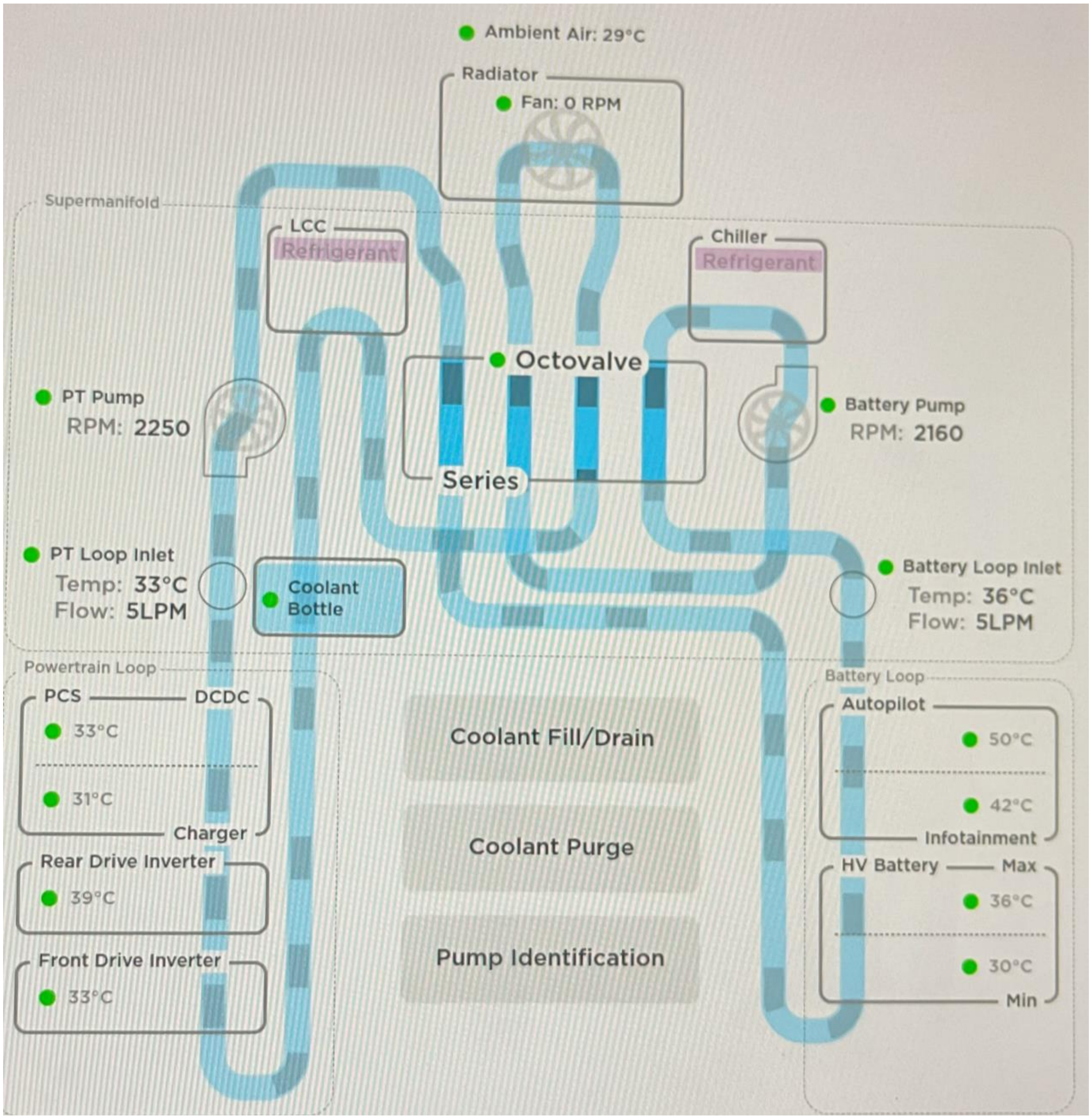
Any resistance in current flow converts to heat. The transistor switch and high current delivery cause high temperatures in the inverter and battery assemblies. In almost all cases, the inverter is liquid-cooled. The early Honda Civic IMA hybrid vehicles didn't liquid cool the transistors, but the system had relatively low output. Most xEVs have liquid cooling plates that remove heat from the inverter's electronics. The transistors use thermal paste or glue to transfer heat to heat sinks. Some repair procedures might include replacing a component that uses thermal paste. For example, Toyota/Lexus recalled early Highlander and RX400h vehicles because of a solder joint that could potentially fail. The technician needed to follow the safety recall procedures to ensure proper replacement technique. Along with general instructions, the procedures indicated proper fastener torque and proper application of thermal paste. If overhauling an inverter, DC-DC converter, or charge controller, any component that uses thermal paste must be reinstalled with the proper coating thickness and coverage.



Cooling channels for he Nissan Leaf Inverter

The inverter cooling system might be shared with other components, such as the motor, DC-DC, charging, and battery assembly. The coolant is circulated by an electric water pump. When servicing a component that results in coolant draining, make sure the system is filled with the proper coolant and the proper bleeding procedure is followed. The service info might have the technician actuate the coolant pump while bleeding the system to ensure there are no air pockets. An air pocket can result in no circulation of the coolant and an overheating concern.

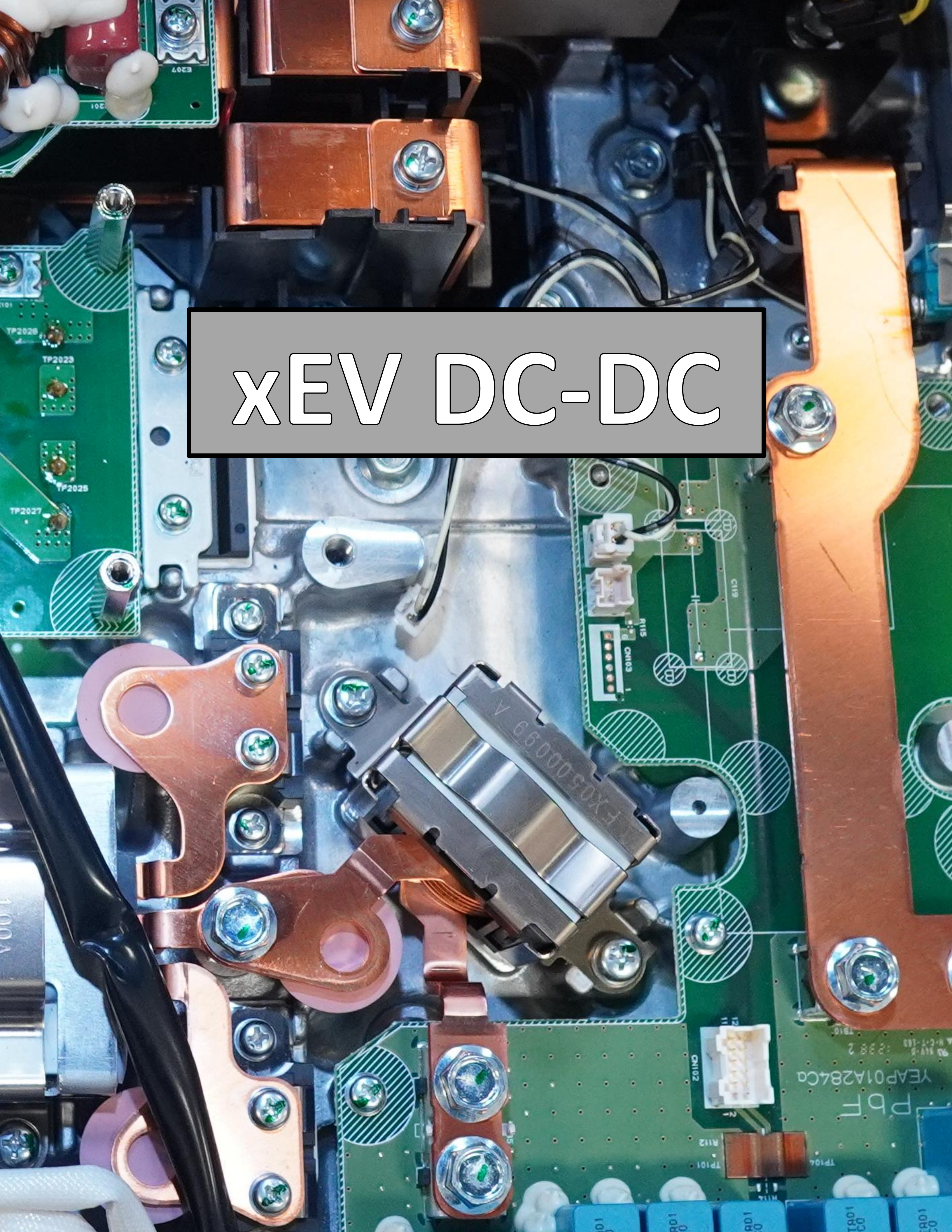
Lexus Cooling channels



Model Y cooling loop. The PCS (DC-DC converter), front, and rear inverter on the same coolant loop

Many technicians use the Airlift (vacuum bleeding) system to ensure the cooling system is completely full and the air is evacuated. With the Airlift system, a technician places the empty cooling system in a vacuum (no air), then connects a coolant fill tube that's purged of all air and is filled with coolant. Then when the Airlift valve is opened, the vacuum pulls coolant into the system. Since the system had no air in it, there was no air to be trapped. The Airlift system is also good for checking for leaks. When the system is placed under a vacuum, if the system cannot hold the vacuum, there is a leak present.

xEV DC-DC



6 – DC DC Converter

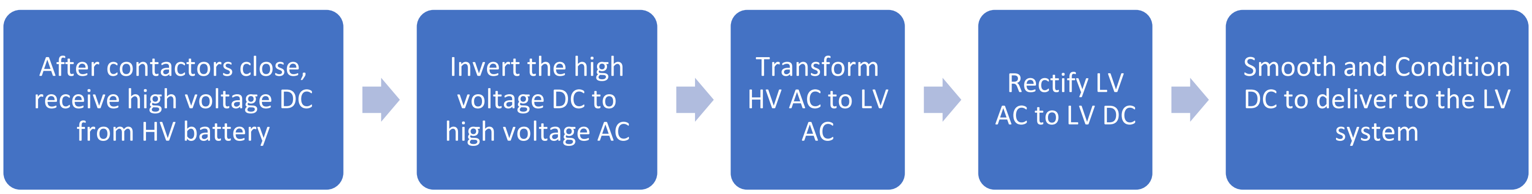
The purpose of the DC-DC converter is to take the high voltage from the HV battery and reduce it to the low voltage operating level. This low voltage will charge the low voltage battery as needed and provide all the power needs for the low voltage components. It essentially takes the place of the alternator (generator) found in a conventional ICE vehicle.

In most xEVs, the low voltage battery is considered an auxiliary battery because it only provides power for initial startup while the computer systems perform their safety checks. As soon as the high voltage contactors are closed, the DC-DC converter will supply all low voltage power needs.

The failing low voltage battery will prevent the xEV from operating if the voltage is adequate to power the modules up and allow the safety check to pass. If the HV contactors do not close, the system will never take advantage of the high voltage battery capacity, which ultimately powers the low voltage system.

Operation:

The process for the DC-DC converter while converting high voltage to low voltage:

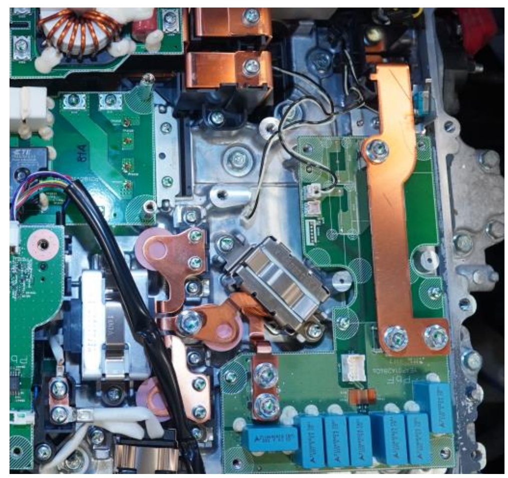


Locations:

DC-DC converter locations vary based on manufacturer and vehicle layout. Often, the DC-DC converter is housed with other components, such as the inverter and charge controllers. One reason for this is to share cooling plates and thermal management devices. The DC-DC converter uses transistors and potentially control large amounts of current. Releasing that heat into cooling plates allows for thermal management.

Removing the lid with the Nissan logo will expose the electronics for the DC-DC converter and the HV AC and DC charger.

Leaf Design – The Nissan Leaf combines the charge controller and DC-DC converter into a single water-cooled package that mounts on top of the motor and inverter assembly.



The components aren't individually serviceable.

Toyota design – The Toyota system packages the inverter and DC-DC converter in an assembly on top of the transaxle. This allows for water cooling for all the high-current transistors that handle high and low voltage.

Many hybrids share this same design. Usually when a DC – DC converter fails and it's part of a combined unit, all of the associated components are replaced as well.

Toyota hybrids packages their DC-DC converter with the inverter electronics. They share the same cooling system.

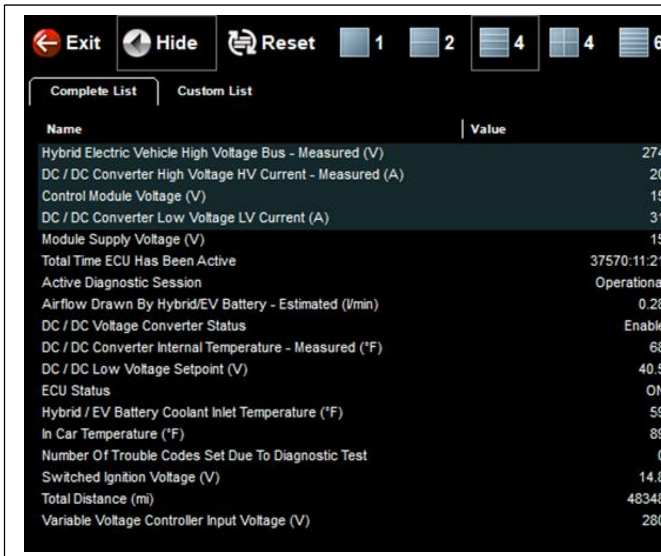
Tesla – tesla combines their DC-DC converter with other high voltage components, such as the contactors, charge controller, and battery management system. The thermal management system brings coolant to the battery and the power electronics.

The DC-DC converter is located in the Penthouse of the Tesla battery. It is liquid cooled and shares space with the charge controller and other HV electronics

Diagnosis:

Diagnostics trouble codes accompany most DC-DC failures, since the system is completely electronic and computer controlled.

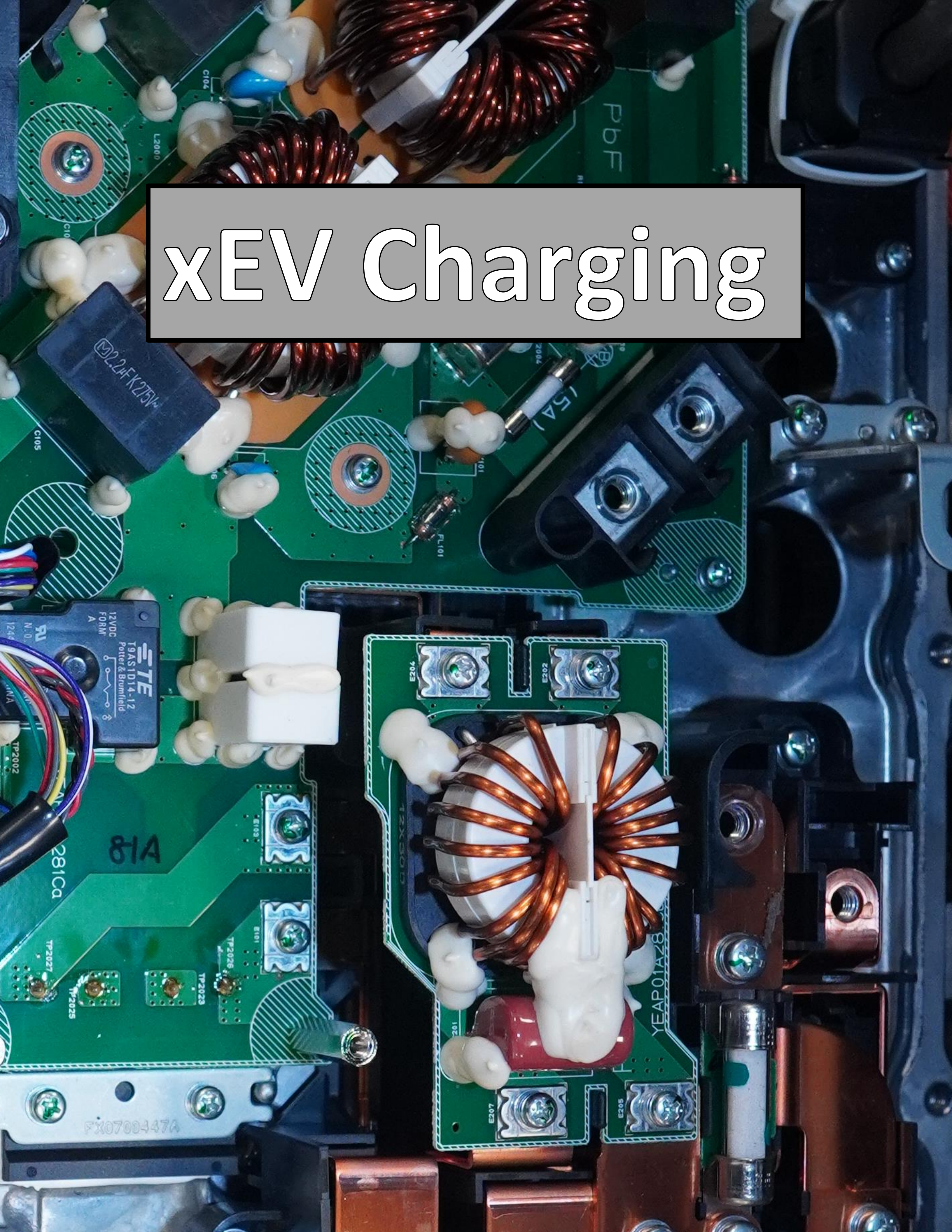
Technicians can check for output by loading the auxiliary battery while monitoring the amperage and voltage output with a scan tool or by directly measuring the output using an ammeter. Most DC-DC converters can output well over 100 amps at 14-16v DC.



Name	Value
Hybrid Electric Vehicle High Voltage Bus - Measured (V)	274
DC / DC Converter High Voltage HV Current - Measured (A)	20
Control Module Voltage (V)	15
DC / DC Converter Low Voltage LV Current (A)	31
Module Supply Voltage (V)	15
Total Time ECU Has Been Active	37570:11:21
Active Diagnostic Session	Operational
Airflow Drawn By Hybrid/EV Battery - Estimated (l/min)	0.28
DC / DC Voltage Converter Status	Enable
DC / DC Converter Internal Temperature - Measured (°F)	68
DC / DC Low Voltage Setpoint (V)	40.5
ECU Status	ON
Hybrid / EV Battery Coolant Inlet Temperature (°F)	59
In Car Temperature (°F)	89
Number Of Trouble Codes Set Due To Diagnostic Test	0
Switched Ignition Voltage (V)	14.8
Total Distance (mi)	48348
Variable Voltage Controller Input Voltage (V)	280

Ford Fusion DC- DC data

xEV Charging



7 - Charging

The high-voltage battery is rated in kilowatt-hours. For example, a PHEV might have around a 20kWh battery, whereas a BEV might have around a 75kWh battery (250+ mile range). Keep this in mind when considering a home charger. The following describes three levels of chargers, how much current they pull from the external power source, and how many kWh of energy they offer the battery.

Level one charging

Level 1

120-volt charging. This is the slowest level of charging since it uses a 15-amp household plug to provide power to the high-voltage battery. 120v x 15amps = 1.8kW at best. Some level one chargers might only consume 12 amps of current, which would reduce the output to 1.44kW. The level one charger could work well with PHEV vehicles, but it’s impractical for BEV vehicles. A depleted PHEV battery requiring 12kWh or charge would take about 7 hours to charge on a 1.8kW level one charger. A 75kWh BEV battery at 20% would take 25 hours to charge to 80% on a 1.8kW level one charger, assuming no energy is needed to condition the battery while charging.

Level two charging

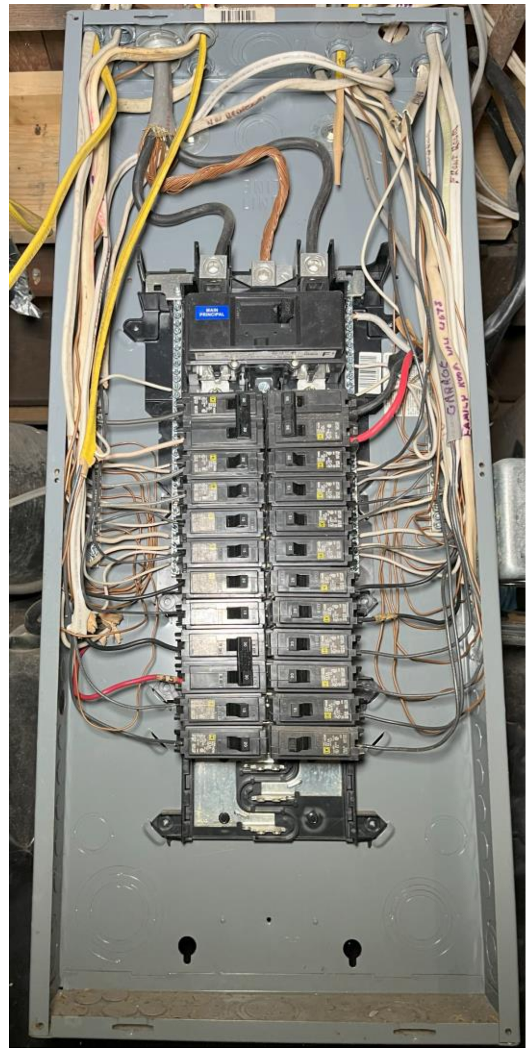
Level 2

240-volt charging. The level two charging uses 240 volts AC to deliver a more practical charging event. The output of level two charging varies from 16 to 64 amps, but the 32-amp (7.7kW), 40-amp (9.6kW), and 48-amp (11.5kW) chargers are most popular for a BEV. The following chart shows the charge time for these three chargers when charging a 75kWh battery from 20% to 80%.

Current from house	32 amp	40 amp	48 amp
The energy delivered to the battery	7.7kW	9.6kW	11.5kW
20 – 80% charge time for a 75kWh battery	5.8 hours	4.7 hours	3.9 hours

The tendency would be to pick the largest charger since it offers the shortest charge time, but some considerations need to be made:

- Can the vehicle accept a high rate of charge? Since the vehicle must convert the household AC voltage to a high-voltage DC, the vehicle needs to utilize an onboard charge controller. The size of this controller determines the charging capacity. If a charge controller can only handle a max of 7.7kW, installing a larger level two charger will not result in a quicker charger. Under these conditions, the charging is vehicle-constrained because it doesn't have a high enough capacity on-board charger. One might still consider a larger charger to "future-proof" the installation because as BEVs become more popular, the charging capacity and costs will improve.
- Can your house provide for a higher level of charging? Having a dedicated circuit delivering high amperage might not be an option without serious upgrades to the home wiring and power distribution. The amount of power your home can handle is determined by the transformer size outside, the entrance cable from the electric company, the breaker panel capacity, the load demands for the entire home, and the wiring and plug from the breaker panel to the charger plug or connection.
- Some manufacturers entice new EV customers by offering to pay for all or a portion of charger installation costs since it could cost between $1500 to $3000 for charger installation, not including any home or electrical system modifications that might be required.



Here is an electrical panel with a few issues. 1 – it doesn't appear that the neutral is bonded to the panel. 2 – it looks like the service entrance cables are too small for the 200-amp breaker, 3- the bare neutral is typically insulated. This panel would fail an inspection.

Level 3

DC fast charging. The level three charging allows for very high charge rates and relatively low charge times. This system is intended for travelers to quickly charge their vehicle when driving long distances. The level three charger output can vary greatly depending on many factors, such as charger type, amount of vehicles at a charging station, battery/vehicle type, battery temperature, and current charge level, to name a few. Common level three charging rates are 150kW and 250kW, but some level three chargers deliver much lower output.

Level three charging

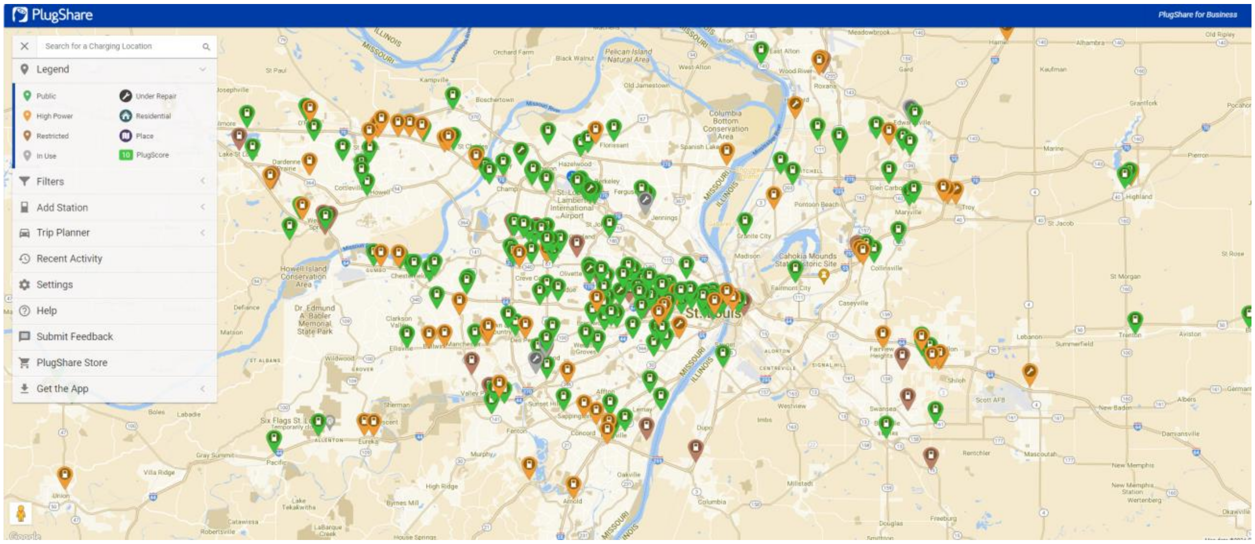
In an ideal situation, when charging a vehicle at a level three charger, the battery would be pre-conditioned to place it at a preferred temperature and a 75kWh battery at 20% would take about 20 minutes at a 150kW charger and about 11 minutes at a 250kW charger to charge to 80%. Those times are not realistic, because as the battery is charging, the level three charger will reduce output as necessary because of the characteristics of battery capacity. The charge rate is also reduced if battery cell or connector temperatures increase beyond acceptable levels.

Arguably, the biggest criticism of EV ownership is the charging experience. Slow charge times, out-of-commission chargers, lack of locations, and overfilled charging lots are major complaints.

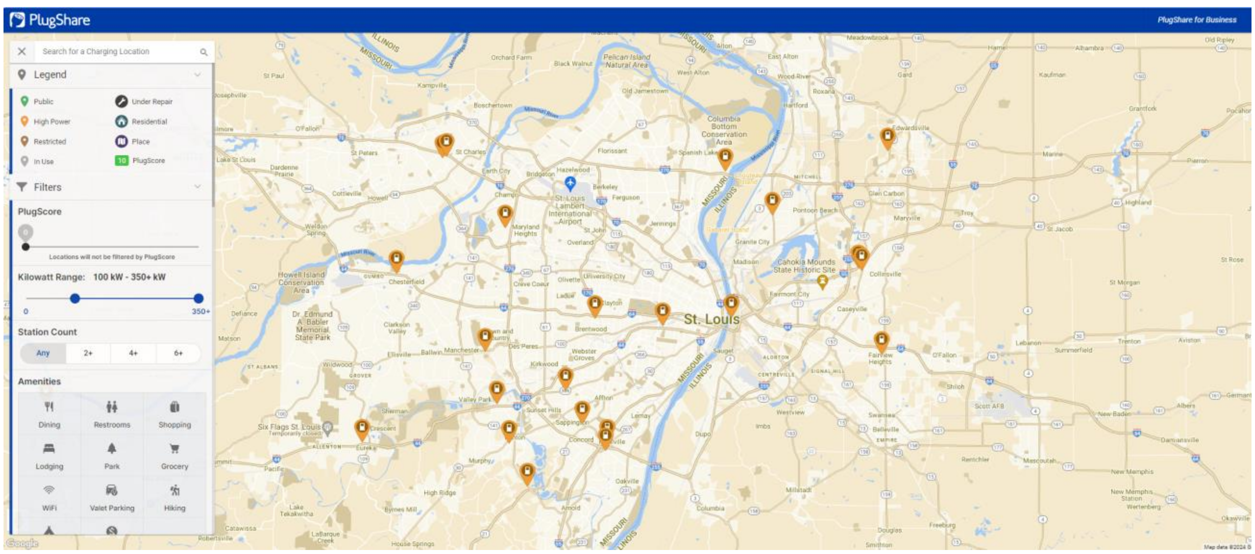
Tesla has the largest charging network and its reliability is 99.95%. In 2023, many manufacturers have committed to using the Tesla-style charging plug (NACS plug) and Tesla will start allowing these vehicles to use their supercharging network.

Other third-party companies, such as EV-Go, Electrify America, and EV Connect have not had great reliability. A study of mostly California Bay area chargers showed that only 72.5% of the chargers were functional. The issues were typically failures with the touchscreen, payment system, charge initiation, network, or broken connectors. Some reports state that EV owners often experience broken EV charging stations requiring additional travel to find another charger. This is a contributor to the "range anxiety" condition many EV owners experience and it is a deal-breaker for potential EV buyers.

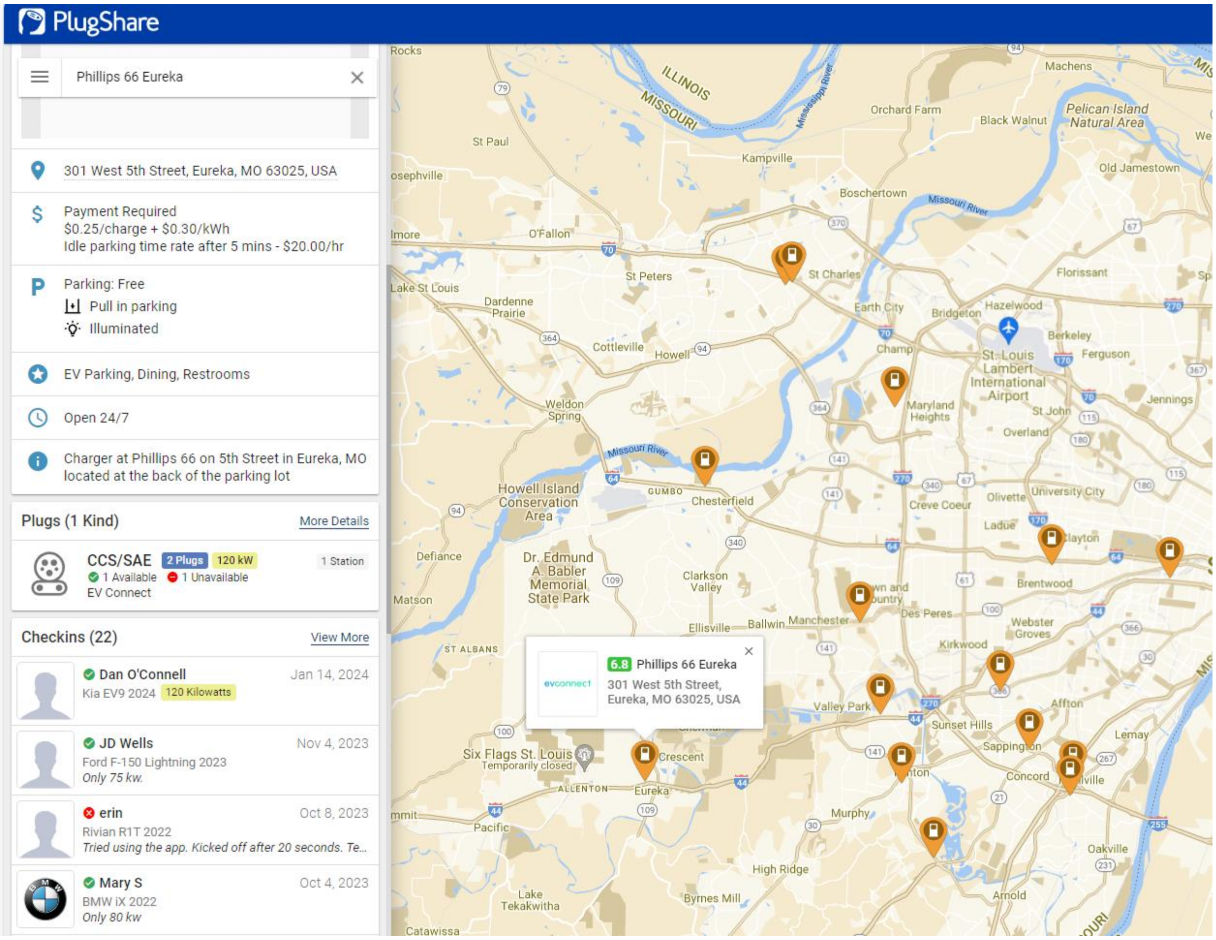
Plugshare.com displays public chargers across the world. Here is a screenshot of the St. Louis region:



After filtering to show chargers between 100kWh and up, this is the result of the high-powered Level three chargers:



Hovering over a destination will show the charger's name and provide a quick rating. If you click on the destination, the panel on the left will provide more information, such as cost, available plugs, occupied chargers, kWh output, and customer reviews.


PlugShare
Phillips 66 Eureka
301 West 5th Street, Eureka, MO 63025, USA
Payment Required
$0.25/charge + $0.30/kWh
Idle parking time rate after 5 mins - $20.00/hr
Parking: Free
Pull in parking
Illuminated
EV Parking, Dining, Restrooms
Open 24/7
Charger at Phillips 66 on 5th Street in Eureka, MO located at the back of the parking lot
Plugs (1 Kind)
More Details
CCS/SAE
2 Plugs
120 kW
1 Station
1 Available
1 Unavailable
EV Connect
Checkins (22)
View More
Dan O'Connell
Jan 14, 2024
Kia EV9 2024
120 Kilowatts
JD Wells
Nov 4, 2023
Ford F-150 Lightning 2023
Only 75 kw.
erin
Oct 8, 2023
Rivian R1T 2022
Tried using the app. Kicked off after 20 seconds. Te...
Mary S
Oct 4, 2023
BMW iX 2022
Only 80 kw
6.8
Phillips 66 Eureka
301 West 5th Street,
Eureka, MO 63025, USA

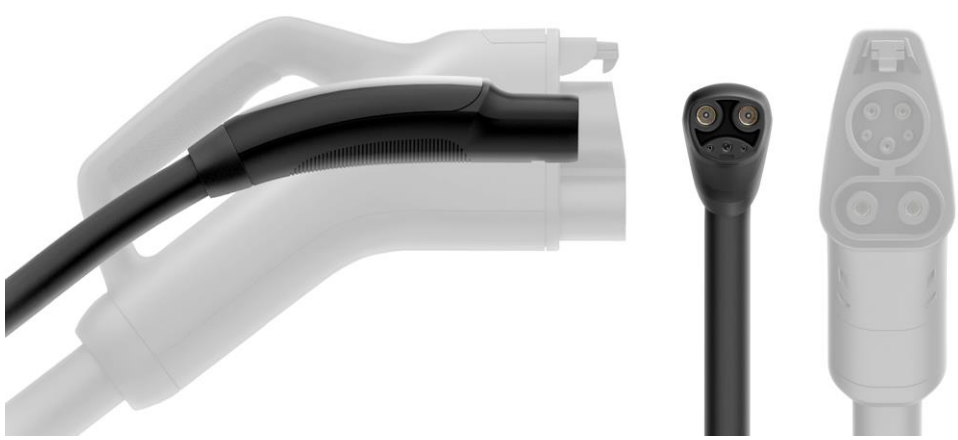
Charger plugs

There are five common charge ports with four being used in the US. SAE developed a standard plug J1772 (type one on image), which most manufacturers adopted up until recently. This connector by itself is only a level one or level two charger and it cannot fast charge a battery. Many PHEVs and some BEVs only have this connection and therefore cannot be fast charged.

The Combo Charging System (CCS) combines the J1772 with two high-voltage DC terminals (third down on image) to allow for fast charging. With the addition of the DC connection, this plug becomes quite large and cumbersome.

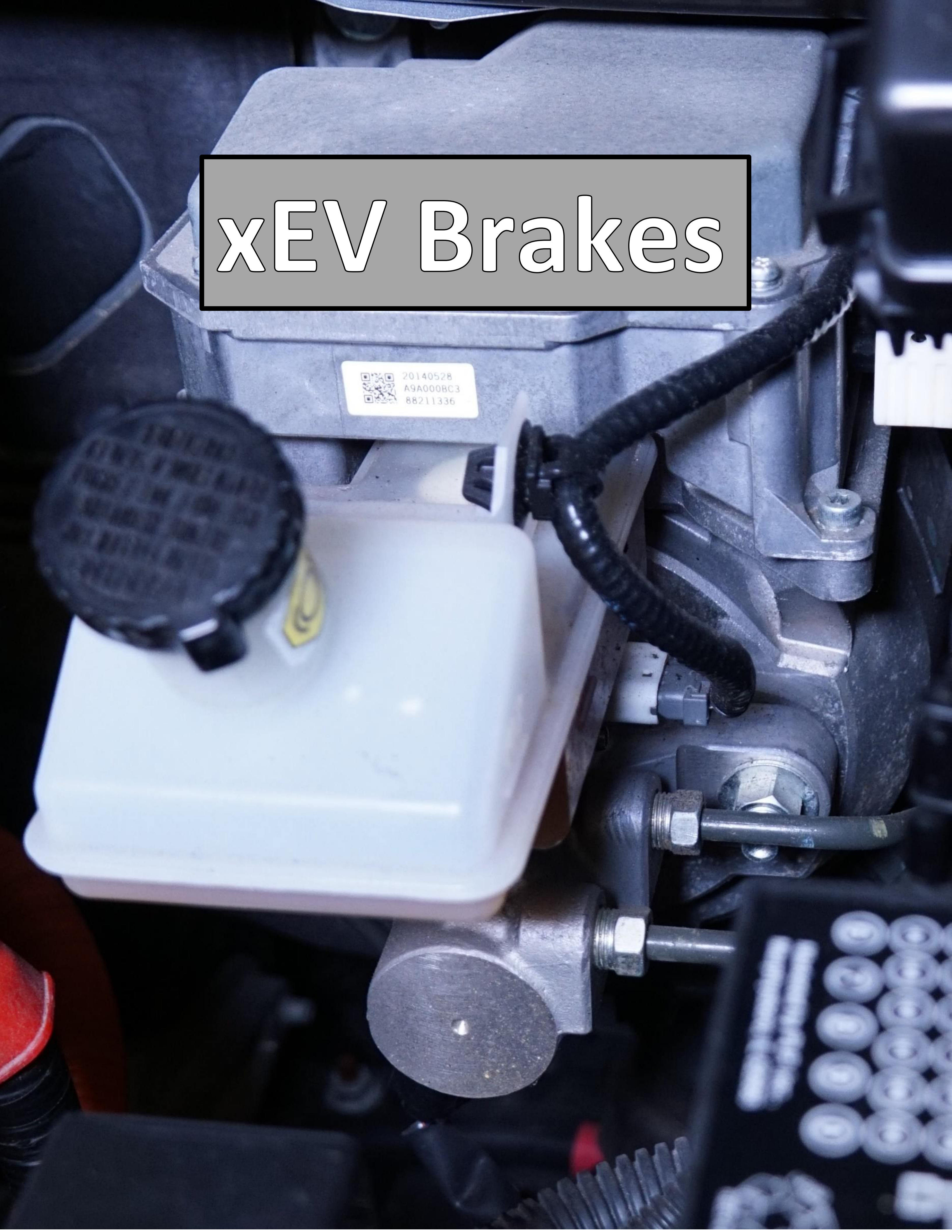
Tesla has its proprietary plug design, which is smaller than the J1772, but yet still allows for level three charging. In 2022, Tesla renamed their charge port to the North American Charging Standard (NACS) and allowed their design and technology to be open access. SAE has designated this plug as the J3400 standard. Soon after providing open access to the plug design, in the US, most manufacturers adopted the NACS connector. As of February 2024, the only BEV manufacturer in the US to not officially adopt the NACS is Mitsubishi.

Another less common connector in the US is the CHAdeMO, which is only used for level three charging. Being a Japanese standard, the CHAdeMO was predominantly used in the US by the Nissan Leaf and Mitsubishi i-MEV, and Nissan has since also adopted the NACS. Of all level three charging options, CHAdeMO is the slowest with a max of about 65kWh.



This image shows the size different between the CCS and the NACS plug. It's obvious why manufacturers have adopted the NACS.

xEV Brakes

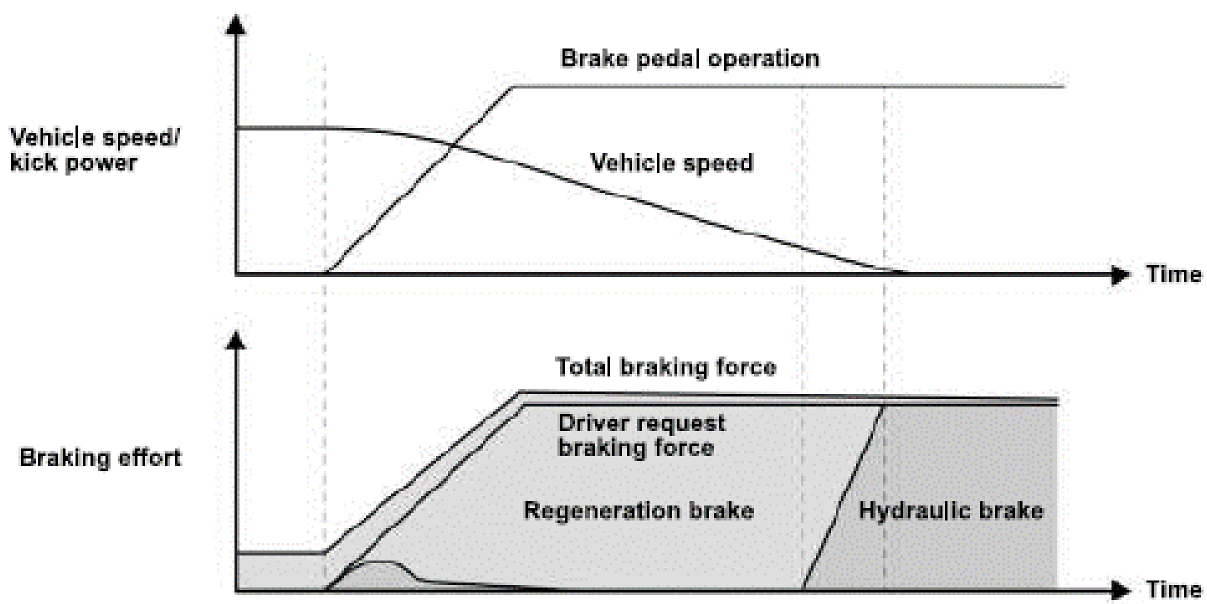


8 - Braking systems

Base brake fundamentals remain the same with xEV braking systems. The brake system still uses four-wheel disc (or disc/drum) brakes that are hydraulically actuated. The braking system still uses vehicle stability control systems (VSC) to control the traction and antilock brake system, and stability functions. The major difference in how the xEV braking system operates is through brake fluid pressure generation and distribution. Unlike a traditional vehicle, when a driver presses on the brake pedal during normal operation, the brake system is not hydraulically actuated. The pedal stroke feels normal and the vehicle braking feels like a typical vehicle, but all of the braking is electronically controlled. For that reason, the xEV braking system is often referred to as electronic braking.

Since the xEV makes the most out of regenerative braking, the braking system is designed to not actuate the hydraulic brakes during braking events unless the vehicle experiences hard/heavy braking or the vehicle is below a speed where regenerative braking won't apply sufficient vehicle deceleration. There are three main modes of electronic braking: Full regeneration, Blended, and Hydraulic.

Refer to the image to see how Honda represents the conditions for each mode.

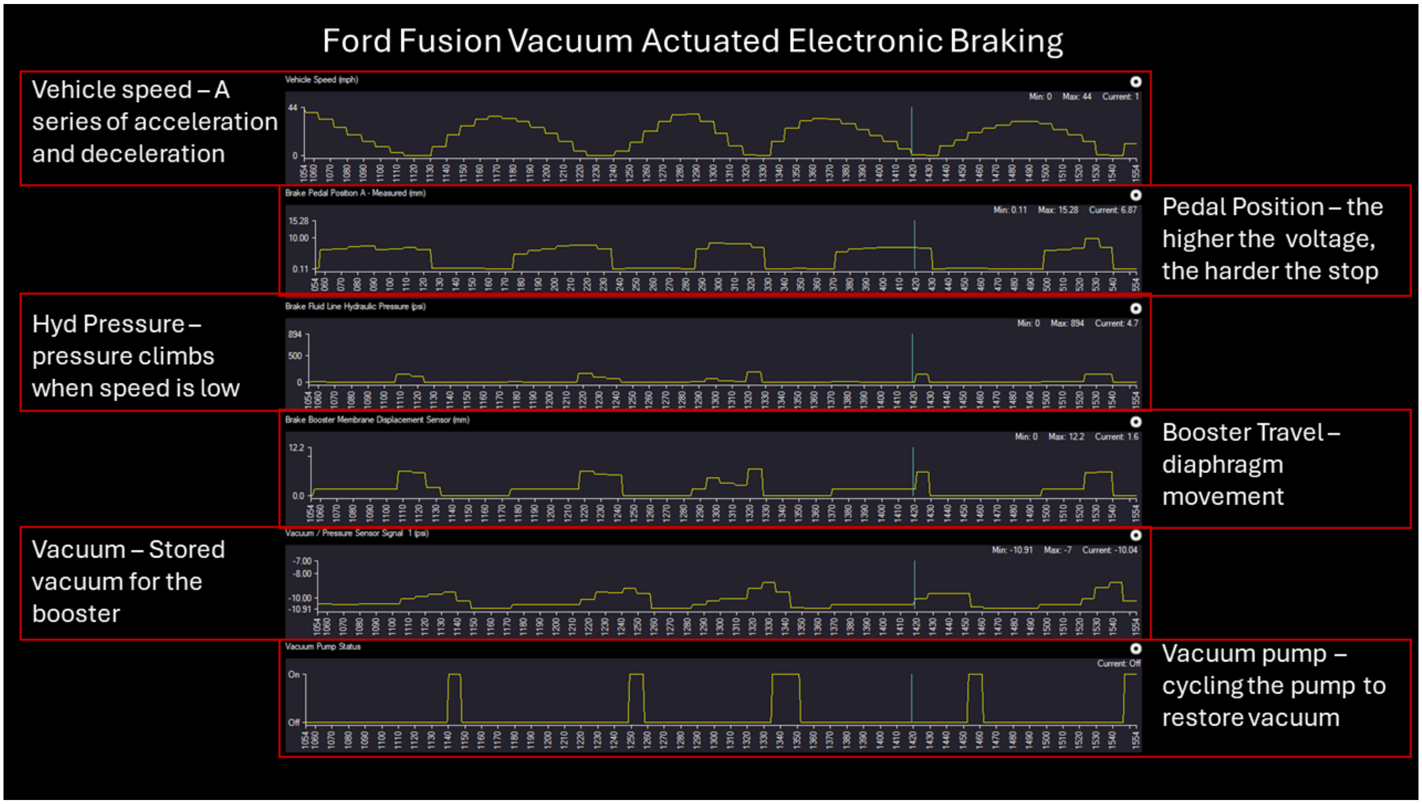


Honda shows the various braking responsibilities of the electronic braking system for a xEV.

Regen vs. Blended vs. Hydraulic

- Under most conditions, a normal/gradual deceleration will result in no hydraulic brake actuation and full electrical regeneration until the vehicle reaches a low speed, likely around 5mph. At that point, the hydraulic brakes slow the vehicle to a stop.

- Under heavy braking, such as a panic stop, the vehicle will still offer brake regeneration, but it will blend in hydraulic braking as needed.
- At low speeds, the vehicle will simply use hydraulic braking.



This recording of braking data from a Ford Fusion Hybrid with a vacuum-actuated electronic braking system shows how the hydraulic brakes activate at low vehicle speeds during normal braking. The recording shows a series of accelerations and decelerations. Key takeaways include the brake pedal stroke compared to the brake pressure. The third braking event displayed increased hydraulic pressure because the pedal was applied harder than the other stopping events. During normal braking, the hydraulic brakes only come on at low speeds, typically below 5mph.

The motor controller and the brake module communicate to allow for this seamless transition between regeneration and hydraulic braking. The braking systems do, however, share many of the same components, such as a brake fluid reservoir, brake fluid level switch, stroke simulator, and brake pedal travel sensor as well as any antilock brake/stability control valves.

Brake Fluid Reservoir

Starting with components that are common with a traditional vehicle. The reservoir simply stores the brake fluid. This braking system may use DOT 3 or 4 fluid and there's a max/min indication on the reservoir. The cap seal is important to prevent moisture from the air from contaminating the system.

Nissan Leaf reservoir and brake level switch

Fluid Level Switch

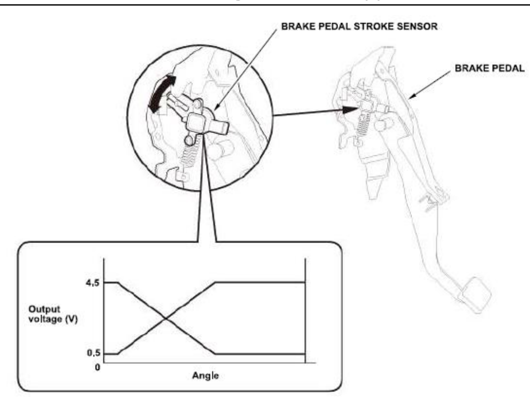
As its name implies, there is a fluid level switch to inform the driver if the brake fluid level drops below the acceptable range. The level may drop due to a leak in the hydraulic system or because caliper pistons have extended out so much that it's forced the level in the reservoir to drop low.

Stroke Simulator

The electronic braking system is designed to feel familiar to the driver. The brake application feel, pedal firmness, and compliance need to feel like a traditional vehicle. The stroke simulator is a device that mimics the feel of a conventional braking system. The stroke simulator allows for master cylinder brake pressure to stroke a "dummy" piston against a spring and/or nitrogen-filled cylinder. These components give the sensation of applying a traditional brake pedal. When braking, to the driver it feels like a normal hydraulic brake, but the pedal and pressure feedback are not doing anything at all aside from feeding the brake controller with pedal travel and pedal speed. When a system failure is detected, the stroke simulator is often bypassed and hydraulic pressure is directed to the wheel brakes.

Brake Pedal Position Sensor

The brake pedal position sensor (BPPS) provides the brake controller with pedal travel and pedal application speed. The controller uses this information to determine if the braking event is typical or aggressive such as in a panic stop. If the controller detects fast pedal application with a long pedal travel, then it can conclude that the driver is in a panic stop situation. During this situation, the brake controller will rely on hydraulic brakes in addition to regenerative braking to bring the vehicle speed down. The braking system might even use "brake assist" where if the driver isn't letting up on the pedal, the brake system can apply even more force than what the driver is offering because of the features of the electronic braking system. The system can monitor the extra effort by concluding that if the driver doesn't let up off the pedal, more braking force is likely desired. Once the driver lifts up on the pedal, then there's no need for additional braking force.



There are many commonalities between different brake systems, but how the brake pressure is delivered to the braking system often differs. There are five different strategies for electronic braking:

1. **Accumulator stored pressure (Toyota hybrid, Ford hybrid, and early Honda hybrid are examples)**
2. **Motor and piston-generated pressure (Hyundai Sonata Hybrid/Ionic 6, Ford Gen 4 vehicles with electronic brake booster)**
3. **Motor-actuated master cylinder (Nissan Leaf, Honda Accord Hybrid, Tesla)**
4. **Vacuum booster controlled through solenoid modulation (Ford Gen 2 and 3 hybrids)**

System one - Accumulator stored pressure

Using the Toyota Hybrid as the example for accumulator stored pressure and solenoid actuated braking, the solenoids pulse width modulate (PWM) brake pressure to the wheel brakes as needed. This allows the hydraulic braking system to remain *off* during normal deceleration until the hydraulic brakes are needed to complete the stop.

Normal Operation

Where this system differs from a conventional braking system is through pressure generation and distribution to the wheels. During normal operation, all braking pressure is generated by an electrically driven pump and stored in a hydraulic accumulator. The system generates and stores approximately 2500 psi. When hydraulic braking is required, this pressure is modulated to the wheels through the linear solenoid valves. For feedback control, the wheel pressure sensor informs the Skid (stability control module) controller of wheel pressures, so it can modulate the linear solenoids as required.

Since the brake pedal doesn't directly influence wheel brake pressure, the system includes a pedal stroke sensor. The stroke sensor simulates a normal brake pedal feel but it only compresses a nitrogen-filled/spring-loaded chamber during normal operation. The switching valve prevents brake fluid from entering the wheel brake circuit and diverts brake pressure to the stoke sensor's piston and housing. When pressing the brake pedal on a Toyota in Ready Mode, the driver is simply cycling the stroke simulator piston.

System two - Motor and piston-generated pressure

Another common xEV electronic braking system includes the use of an electric motor-driven piston to generate pressure for the braking wheels.

Pedal-Driven Master cylinder: Pedal-operated master cylinder generates pressure to stroke a stroke simulator. This master cylinder will also generate all braking pressure when in failsafe mode. Like the accumulator design, the pedal-driven master cylinder is isolated from the wheel brakes from "cut" valves.

Motor-driven Master Cylinder – The motor-driven master cylinder generates wheel brake pressure during normal braking application. The ECU actuates the 3-phase motor to rotate a "ball screw" that moves a piston to apply hydraulic pressure to the hydraulic system. The motor can rotate in either direction, allowing it to increase and decrease pressure quickly and accurately.

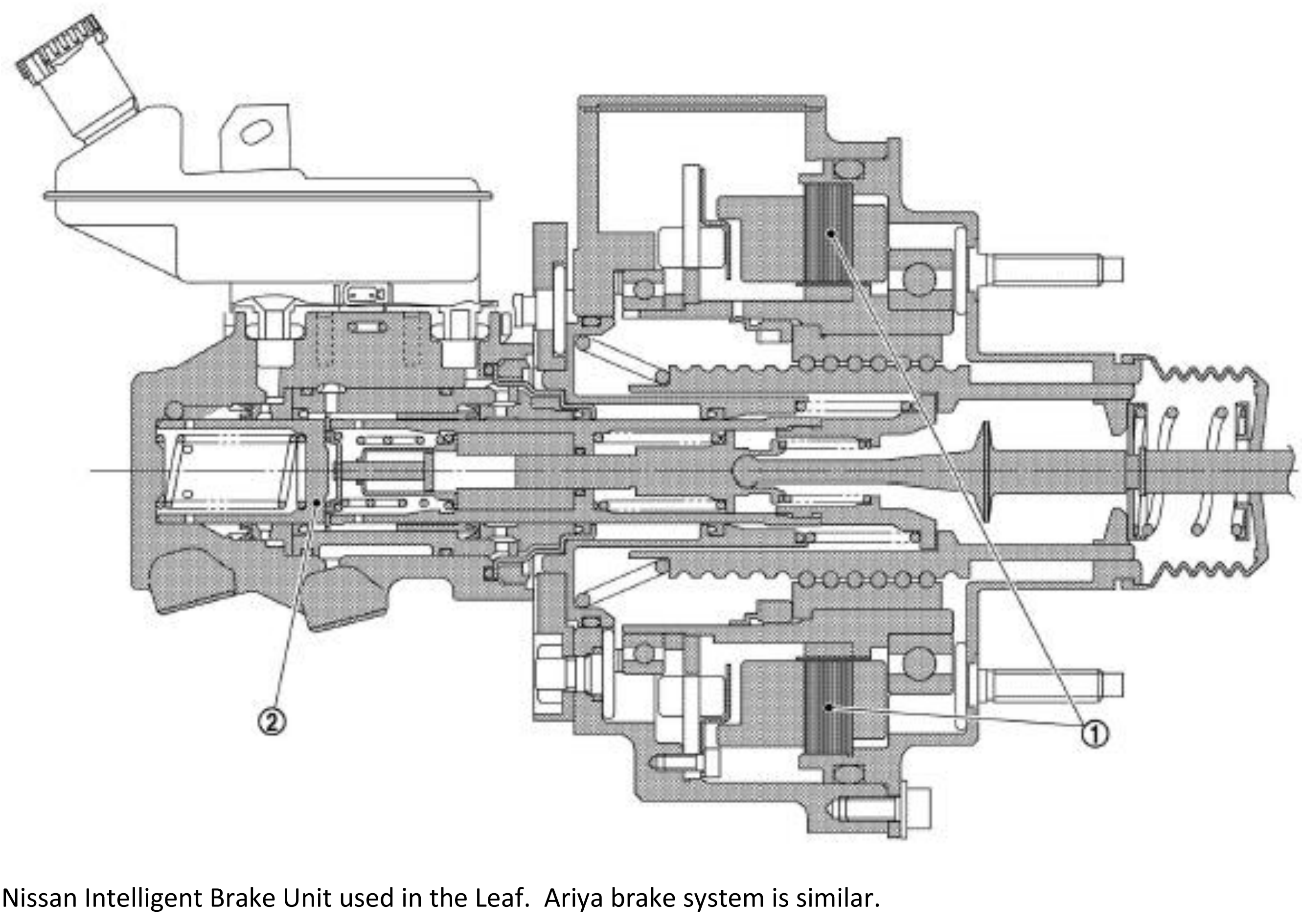
System three - Motor-actuated master cylinder

A close variation to the motor and piston-type electronic braking system is the motor-actuated master cylinder. The motor-actuated master cylinder uses a 3-phase motor to mechanically operate a master cylinder. There are two variations of this system: 1, the motor can actuate the pedal-actuated master cylinder or 2, it can actuate a secondary master cylinder.

This popular system is used by Nissan EVs, such as the Leaf and Aryia, late model Honda Hybrids, such as the 2023 Accord Hybrid, and Tesla vehicles.

Type one

The Nissan Leaf's Intelligent Brake Unit (IBU) is an example of a motor-actuated master cylinder that acts on the pedal-actuated master cylinder. The system looks similar to a conventional vacuum booster but in place of a vacuum booster, a 3-phase AC motor with a recirculating ball screw controls the master cylinder pistons.

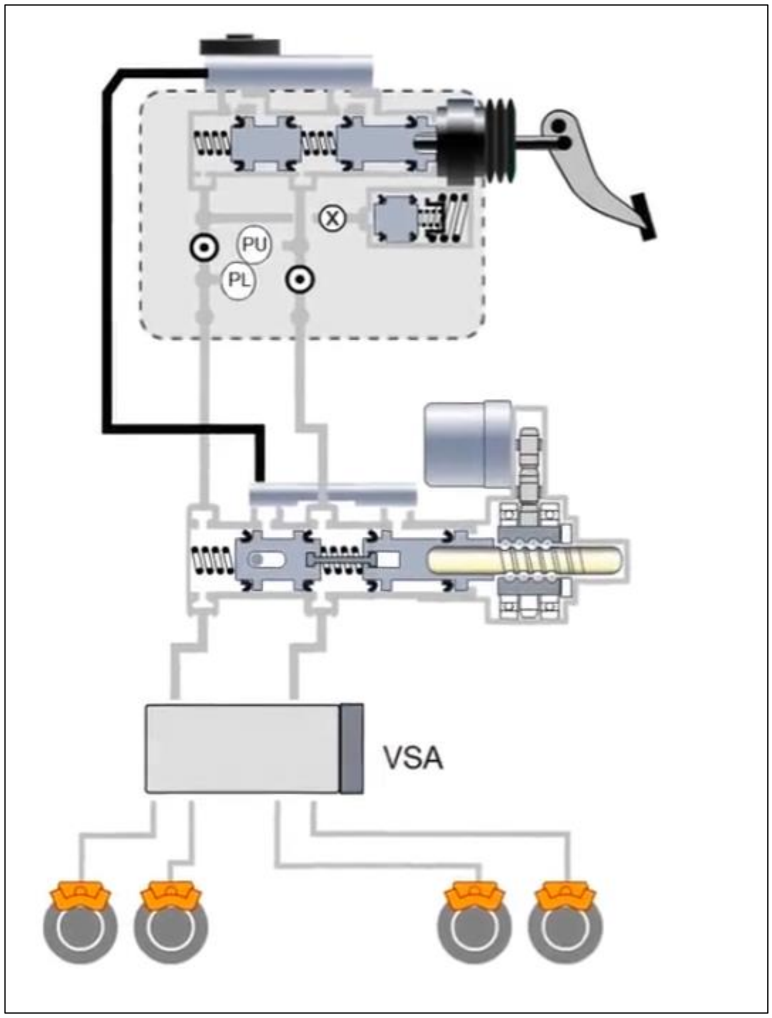


Nissan Intelligent Brake Unit used in the Leaf. Ariya brake system is similar.

Type Two

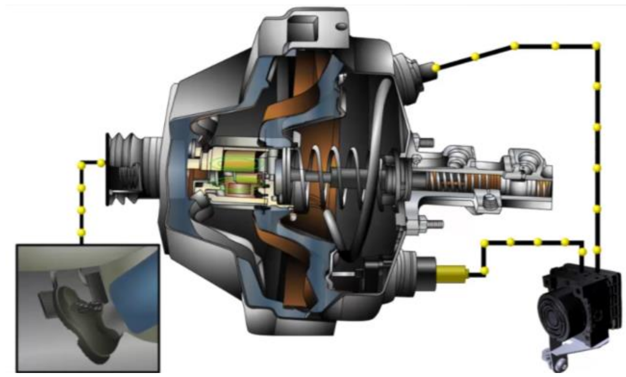
Another design of motor actuated master cylinder involves using a motor that operates a secondary master cylinder to control the wheel brakes. This design uses a primary master cylinder that's connected to the brake pedal and a separate <u>secondary</u> master cylinder that an electric motor actuates to control the actual braking. The primary master cylinder provides the braking force during failsafe operations.

2023 Honda Accord uses this variation of the motor-driven master cylinder.

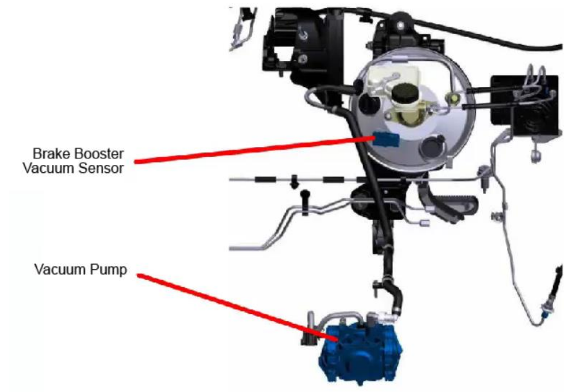


System five - Vacuum booster controlled through solenoid modulation

When comparing a conventional braking system to an electronic braking system, the closest resemblance is the Ford vacuum booster-controlled hybrid braking system found on generation two and three hybrid braking systems. This braking system contains a seemingly conventional brake pedal, an advanced brake vacuum booster, a common master cylinder, a stability control HCU, and an ABS module that controls the system and communicates with other modules. The system resembles an ordinary braking system, but it has a few key differences that allow



Vacuum Booster Electronic Braking – 2^{nd} and 3^{rd} generation Ford Hybrid braking system



Ford vacuum booster electronic braking uses a vacuum pump, vacuum pressure sensor, vacuum booster position sensor, and a brake pedal travel

This type of electronic braking system doesn't contain a stroke simulator in the hydraulic master cylinder or HCU. With this design, the stroke simulator is simply a spring built into the brake pedal. During normal operation, the brake application doesn't necessarily result in hydraulic pressure, similar to other systems, but the stoke simulation is provided by the pedal assembly.

When the hydraulic brakes are required, the ABS module pulse width modulates the vacuum boost solenoid to allow atmospheric pressure into the booster. This pressure differential in the booster causes a mechanical force on the master cylinder's piston which then increases the braking system's hydraulic pressure. The more pressure differential in the booster, the greater the braking force. The ABS module is in complete control of wheel braking.

If there's a need for intervention, the ABS HCU can operate its hydraulic pump and actuate the valves like a typical antilock or traction control situation.

Since this system mimics a normal braking system, there are not many unique service routines.

xEV HVAC

9 - Thermal Management

The thermal management system is essential to the proper operation of an xEV. The active cooling and heating system integrity is absolutely required for a normally functioning vehicle. In addition to the vehicle's cabin, the power electronics, motor, and battery require cooling and heating. At high temperatures, lithium-ion batteries degrade faster and have less output. At low temperatures, lithium-ion batteries have poor performance and charge at lower rates. It is generally stated that lithium-ion batteries prefer the same temperatures as people. The thermal management system serves to maintain proper temperatures for the battery systems.

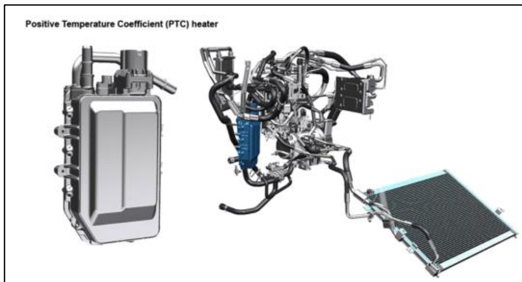
The power electronics generate heat through electrical resistance. Although the power electronics are very efficient, the lost efficiency results in heat. The fast switching and high current nature of the power electronics results in high temperatures that require active cooling.

The electric motors not only generate heat through friction but also through electrical resistance and the eddy currents found in the rotor and stator core. The motor typically releases the heat into the lubricating oil which is then transferred to liquid coolant. It is essential to keep the heat down in electric motors to prevent the permanent magnets from losing their magnetism. Also, higher heat causes higher electrical resistance, which not only results in more heat, but also reduced motor performance.

In a basic thermal management system for an xEV, the heating is performed by one or a combination of methods

Heating - Engine thermal waste

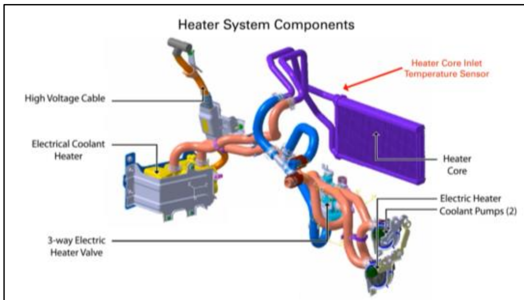
Engine coolant from an HEV or PHEV can provide the necessary heat to xEV components from the ICE's waste heat. ICE engines are at best +/-35% efficient. The majority of energy from an ICE is lost as heat through the exhaust or cooling system. This attribute can benefit an EV that needs heat to keep a battery warm or to warm the cabin during cold weather operations. A BEV has to generate most of its heat to warm the battery and control the climate in the cabin. This results in lost vehicle range.



PTC Heater from Ford Lightning

With PHEV vehicles, it's common to have valving that directs heated coolant between the EV components and the cabin as necessary.

Heating - PTC Heater



PTC Heater from Honda

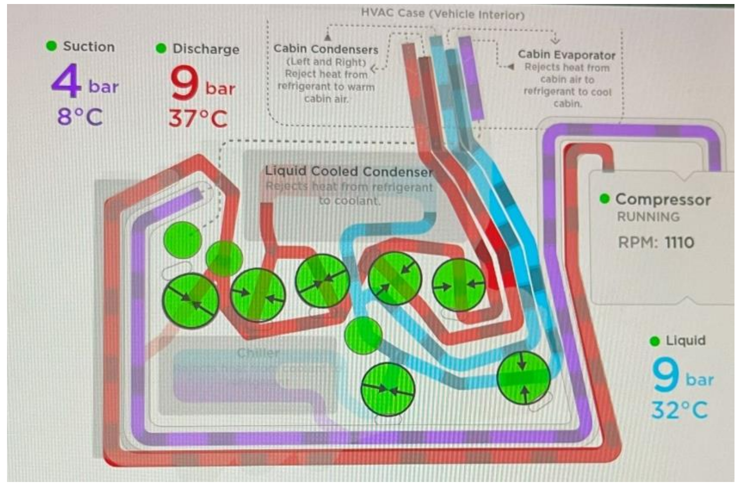
The HEV/PHEV/BEV might use a positive temperature coefficient (PTC) heater which uses electrical heating elements that increase resistance as current flows. Resistance in an electrical circuit releases heat. This type of heater is considered 100% efficient since all voltage must be dropped across the resistor and the electrical energy is converted to heat.

The PTC heater could be low-voltage/high-current, or high-voltage/low-current. The xEV is more likely to use a high-voltage/low-current PTC, but in the case of some vehicles, such as the Honda Accord Hybrid, the auxiliary cabin heater utilizes four low-voltage/high-current PTC resistors controlled by relays.

As stated, the PTC heater might rely on physical conduction for heat transfer, such as in the Nissan Leaf battery pack, or it might conduct through coolant heat transfer, which is most common.

Heating - Heat Pump

Heat pumps are gaining popularity in BEVs. A heat pump uses the properties of refrigerant to move heat from one place to another. In the case of adding heat to the xEV components, the heat pump will transfer heat gathered from an outside source (air) and transfer it to the cabin or xEV components. It commonly works in conjunction with liquid coolant pumps and transfers the heat to liquid coolant, which then subsequently transfers heat to the xEV component. The heat pump is two to three times more efficient than a PTC heater.

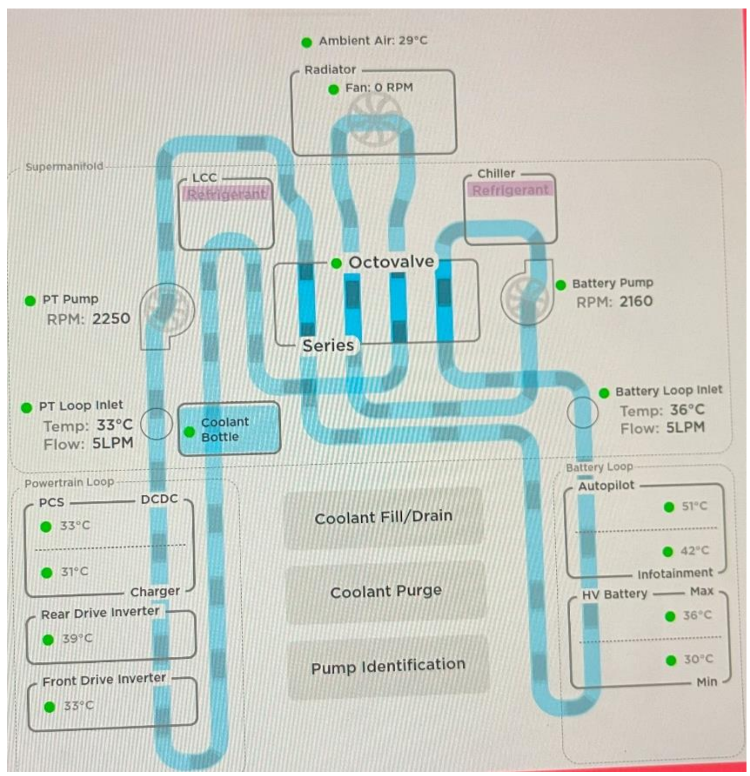


Tesla's heat pump with their super manifold and Octovalve make for an impressive HVAC system that can provide heat and cooling simultaneously to just about any component that's part of the cooling loop.

The thermal management system also controls the cooling of xEV components through one of the following methods:

Cooling - Radiator and Pump

The cooling system could include liquid coolant, an electric pump, and a radiator, similar to an ICE cooling system. The circulation pump can activate to move heat from the xEV components to the radiator. The system might include bypass or



The Octovalve can switch the flow coolant to five different paths depending on demand.

diverter valves to allow the system to cool one or multiple components.

Cooling - AC compressor

An electronic air conditioning compressor can “chill” an evaporator that has liquid coolant flowing through it. This chilled fluid is directed through manifolds or diverter valves to xEV components that need cooling.

Cooling - Heat pump

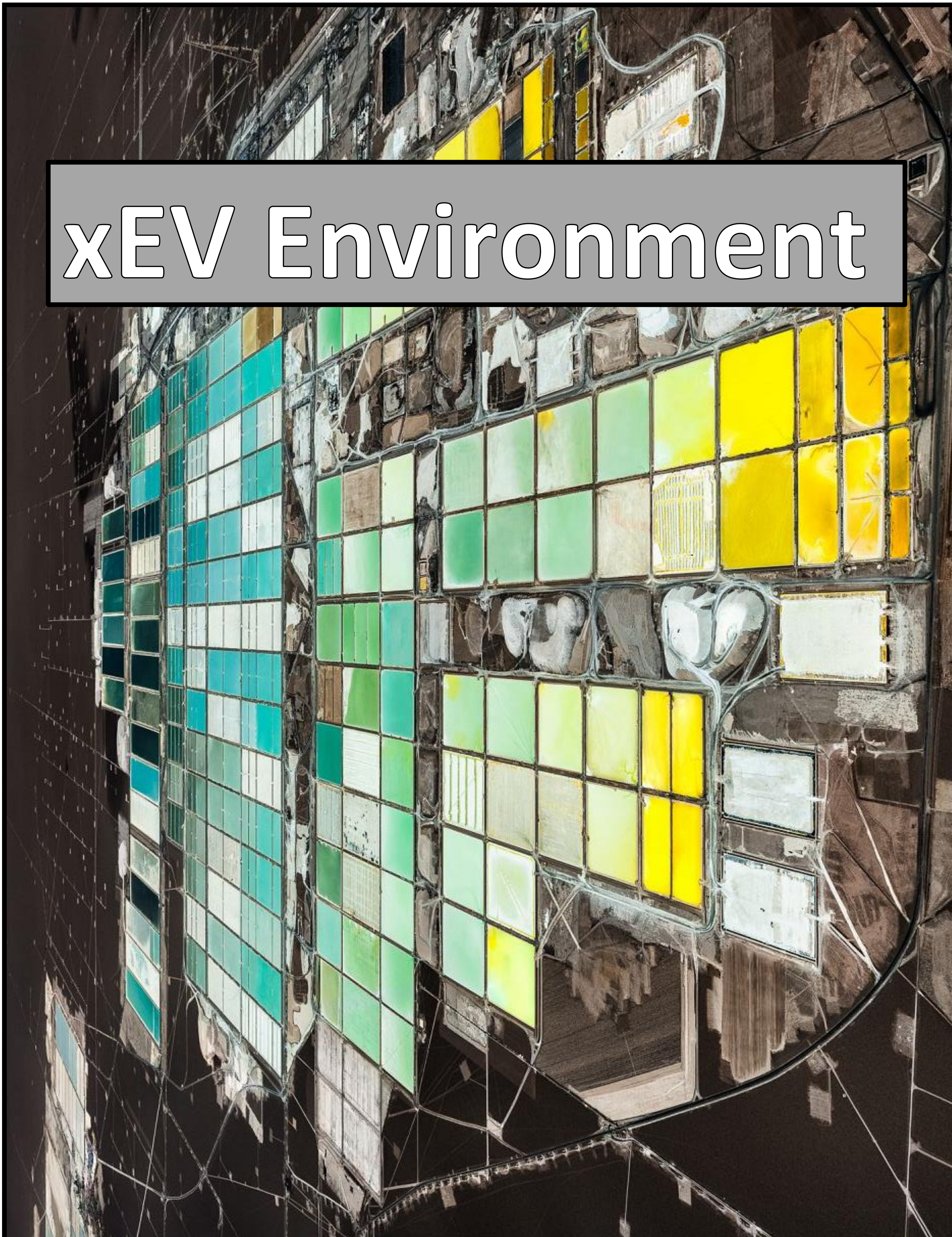
The heat pump is similar to a conventional AC system in that it uses refrigerant to exchange heat. For the sake of cooling, the heat is removed from the xEV component through a liquid evaporator and then it’s released through either a liquid condenser or radiator type condenser or possibly both. The heat pump is an advanced system that allows for heating and cooling multiple components simultaneously by directing coolant flow through either condensers or evaporators. The systems are gaining popularity for fully electric vehicles because they use much less energy than conventional PTC heaters and AC compressors. The heat pump systems are typically 2 to 3 times more efficient than using a PTC and conventional AC compressor.

Ideal Temperatures

In a perfect scenario, the thermal management system would maintain the following temperatures.

- Power electronics: Below 60 degrees C (140 degrees F)
- Electric Motors: Below 60 degrees C (140 degrees F)
- High voltage battery: Between 15 degrees C (59 degrees F) and 35 degrees C (95 degrees F)

xEV Environment



10 – Environmental Impact

The environmental impact of electric vehicles is always headline news. There are many claims against the production of xEV, some hold truth, but most are stretches of the truth or flat-out false.

Claim #1 – a: they are very expensive, b: they start on fire, and c: Batteries are not recyclable.

A - They are very expensive as noted in section three. It's expected that the price of the HV battery will reduce significantly over time as it already has over the past decade.

B - They can start on fire if not management properly. Also as addressed in section three, some chemistries can fuel their own fire with oxygen, so controlling a lithium-ion battery fire is difficult and uses a lot of water. Some chemistries, such as LMF, don't react as violently as other chemistries, and therefore are considered a safer battery.

C - HV batteries ARE 95%+ recyclable. One of the beauties of using a battery for energy storage is that all of the minerals that went into construction of the battery are still present after that battery is spent. The recycling process can separate the elements and prepare them for a new life in a new battery. Similar it the manner that low voltage batteries are recycled. The following are businesses that recycle batteries:

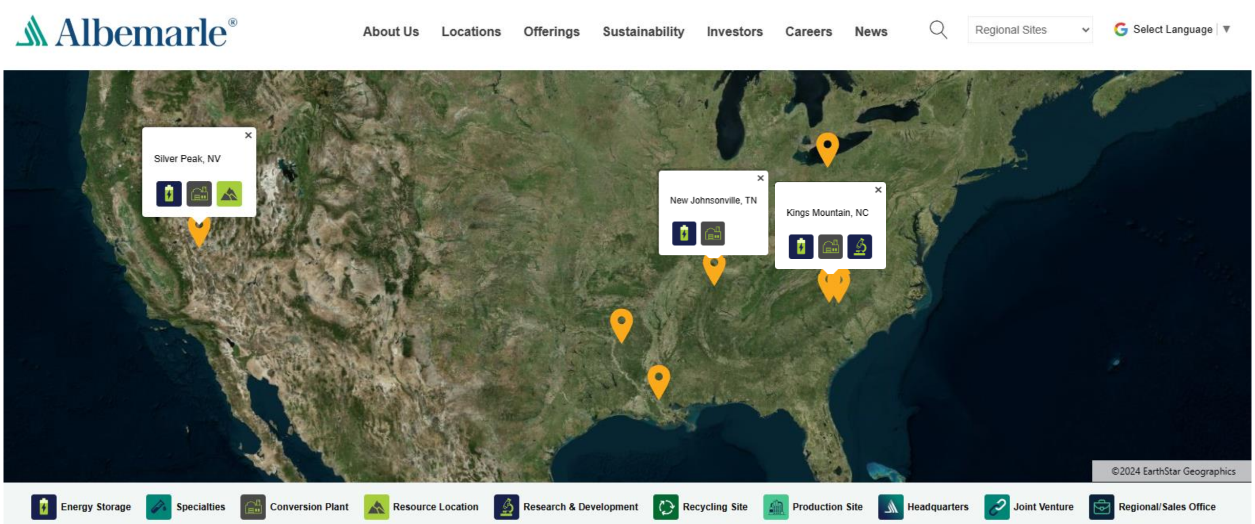
https://www.lithiontechnologies.com
https://www.cirbasolutions.com
https://www.call2recycle.org
https://www.globaltechenvironmental.com
https://www.redwoodmaterials.com

Claim #2 – Mining is a problem. Not enough minerals in the world to build enough batteries

Mining poses a lot of issues regarding the battery manufacturing for an xEV. Most of the battery material comes from outside the US. There is proof of human rights violations surrounding the extraction on Cobalt in the Congo. In South America, Lithium evaporation ponds are polluting the landscape and water supply in additional to taking up vast resources in land and water.

All mining has consequences regardless of the ultimate product usage. The hope is that safer alternative elements replace the resource intensive elements in the battery. In the distant future, battery recycling will help offset the mining in a similar fashion to aluminum and iron. There will be great demands on battery related elements and copper in the near future if the world converts to high energy batteries.

The resources are available to support xEV growth, but most of the battery resources will come from outside the US. New mines in the US require permitting and approval and often takes a decade or longer. There are large lithium deposits in the US, but environmental regulations make it less appealing for mining.



[Albemarle | Locations | All the Elements for a Better World | Albemarle]

[Proposed Mine Global Specialty Chemicals Company | Albemarle Kings Mountain]

Claim #3 – Emissions: EVs emit more emissions than comparable gas vehicles

The math doesn't add up on this claim. The EPA published a study of "Greenhouse gas emissions from a typical passenger vehicle." Document Display | NEPIS | US EPA The following is a summary of the findings:

CO_2 emissions from gasoline and diesel ICE:

- CO_2 Emissions from a gallon of gasoline:
  - 8,887 grams CO_2 / gallon
  - Gas vehicle average 25mpg emits **355.48 gm/mile**
- CO_2 Emissions from a gallon of diesel:
  - 10,180 grams CO_2 / gallon

CO_2 emissions from electricity used by electrical vehicles:

- Average common EV 32kWh per 100 miles or .32kWH per mile
  - .32 x 368 (average US CO_2 emission per kWh of electricity generated)
- 118 grams CO_2/mile

Results:

355 grams CO_2/mile (gas) or 407 grams CO_2/mile (diesel)

Vs

118 grams CO_2/mile

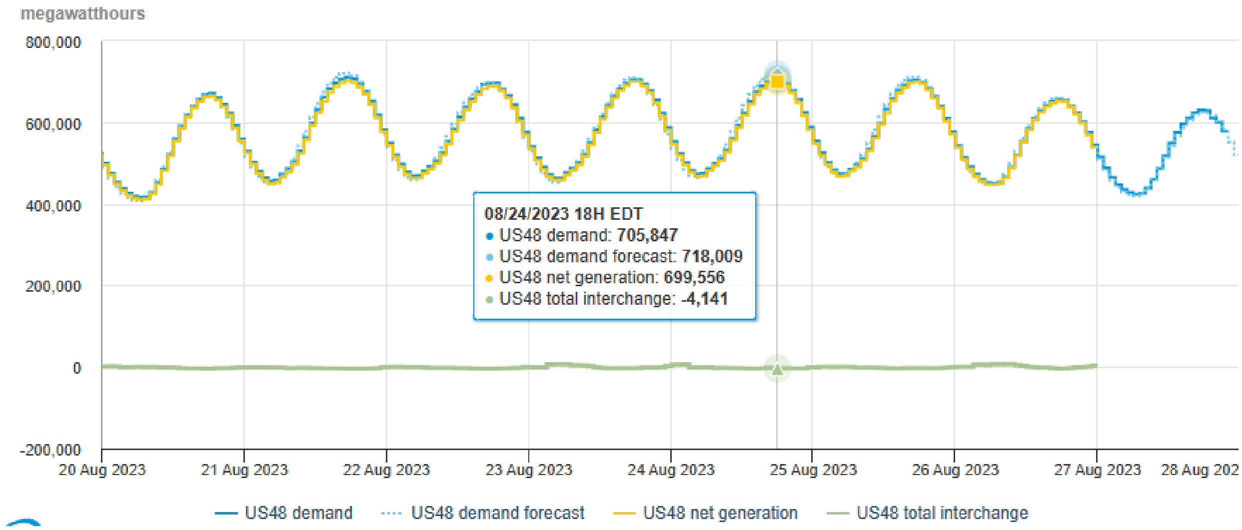
Other factors to consider:

- Lower carbon power generation is coming online ever year, so these numbers will only get betterhttps://ember-climate.org/
- The US generates:
  - 60% of its electricity from fossil fuels:
  - 19% (828 TWh) from coal
  - 39% (1,695 TWh) from gas
  - 0.9% (40 TWh) from other fossil fuels
  - Wind and solar 15% (644 TWh)
  - Nuclear 18% (772 TWh)
  - Hydro 5.9% (251 TWh)
  - Bioenergy 1.2% (52 TWh)

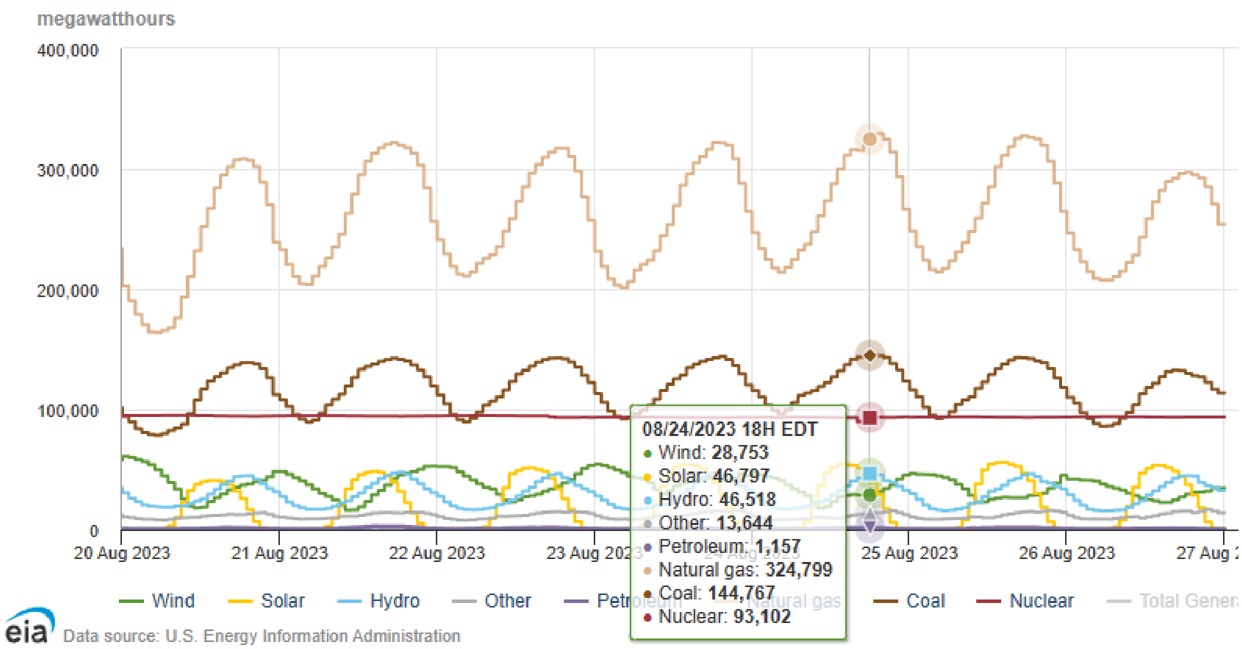
Claim #4 – Power grid - the power grid a: cannot handle the EV revolution, and b: charging a vehicle is more expensive than liquid fuel

A – This Grid monitor shows how much power is generated in the US (48 state) and what source provided that power. It's a remarkable website!

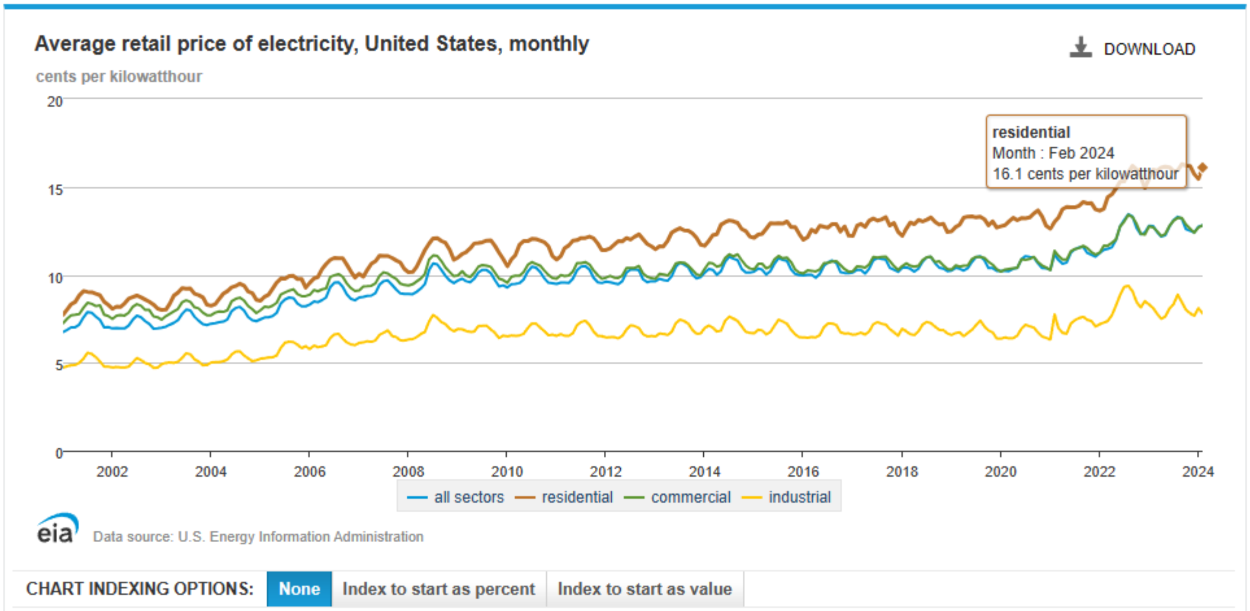
U.S. electricity overview (demand, forecast demand, net generation, and total interchange) 8/20/2023 – 8/27/2023, Eastern Time



U.S. electricity generation by energy source 8/20/2023 – 8/27/2023, Eastern Time



B: Charging an EV is usually about 1/4 to 1/3 the cost of liquid fuel. The variance depends on the cost of electricity and the xEV efficiency.



Pricing example using the average residential electricity costs of $0.161 per kWh.

Tesla Model Y with 320 miles of range.

- 80% of the complete range is 256 miles.
- 20% of the complete range is 64 miles.

Driving this tesla from 80% to 20%(60% drop) would be 192 miles.

The battery is 75 kWh and 60% of the battery capacity would be 45 kW,

If the price per kWh is $0.16 multiplying that times 45 kW would cost $7.20 to charge from 20% to 80% and gain 192 miles of range.

Current fuel costs in Southern Illinois are around $3.80 per gallon of low octane. At this gasoline price, the EV costs would get you 1.89 gallons of fuel, which would make the Tesla have the equivalent of 101.6 mpg.

The larger and more inefficient the EV or the higher the electricity rates, the lower the savings.

It's possible if you are paying Hawaii costs of $0.40 per kWh, and you have an inefficient vehicle, that the EV might cost more to operate.