PEVs and Charging Technologies
Dr. David Tuttle

- Vehicles
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Vehicles

Electric vehicles are not a new concept. Thomas Edison and others were developing electrically driven vehicles over a century ago. However, throughout the 20th century, the key technologies were not available to enable PEVs (Plug-in Electric Vehicles) to offer competitive range, cost, and convenience of a gasoline powered internal combustion engine (ICE) vehicles. Over the past 20 years Lithium batteries, semiconductor-based power electronics and software advanced sufficiently to enable mass-market viable and compelling PEVs such as battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs). BEVs are the most conceptually simple PEVs to understand: a large on-board battery is charged from the grid, the energy stored in its battery is transformed from DC to AC via the power electronics based upon driver commands, and the output from the semiconductor-based power electronics is used by the electric traction AC motor to propel the vehicle down the road. As battery costs have declined substantially over the past decade, BEVs have become progressively more compelling with higher performance, much longer range, and far faster DC-Fast Charging (DCFC) rates.

Plug-in Hybrids use an innovative but somewhat more complex combination of a BEV's electric drive with an on-board gasoline generator or "range extender". The PHEV is also charged from the grid and then driven on electricity until the battery is depleted. Once the battery is exhausted computers seamlessly deploy the gasoline engine to power the vehicle in a fuel-efficient hybrid "charge sustaining" mode to allow the driver to travel long distances without becoming stranded. The PHEV driver can electrify most If not all of their daily local commuting trips and leverage the existing gasoline infrastructure when taking a longer trip. Some past implementations of PHEVs have had a relatively short all-electric-range (AER) that leads to less electrification of trips. Studies show that with longer AERs, far more vehicle miles traveled can be electrified (insert Gil Tal/Thomas Bradley studies reference) and drivers are more likely to charge from the grid instead of driving on gasoline. In August 2022, the California Air Resources Board adopted their Advanced Clean Car 2 (ACC2) regulations that require all vehicle to be BEVs, H2FCVs, or PHEV-50s by 2035 (https://electrek.co/2022/08/25/ca-finalizes-2035-gas-car-ban-a-huge-deal-but-why-not-sooner/). Up to 20% of these vehicles can be PHEVs as long as they have a minimum of 50 miles AER. This 50-mile electric range should comfortably cover the average daily commuting distance in the US of ~35miles (find NHTSA/NHTS reference). PHEVs eliminate the century-old range anxiety and charging infrastructure concerns. A range extender may be particularly valuable for vehicles such as pickups that haul heavy payloads or tow trailers or for drivers in rural areas that have sparse DC-Fast Charging (DCFC) infrastructure.

As hydrogen (H2) related costs continue to improve, H2FCV (hydrogen fuel cell vehicle) technology will likely be adopted in larger trucks that consume considerable amounts of fuel, have the heaviest payloads or trailer, need fast refueling times, or travel very long distances. Large Class-8 Semi trucks for long distance hauling and heavy local refuse trucks are examples of applications where hydrogen has an advantage with its relatively high speed of refueling and high energy density of on-vehicle fuel storage tanks.

As a wider variety of compelling BEV and PHEV models have become available, adoption has substantially increased (insert data and reference on PEV adoption). As battery technology further advances and becomes less expensive, more charging infrastructure is deployed, and a wider variety of models is available electric vehicle adoption is expected to continue to accelerate.

Charging Infrastructure

A charging infrastructure that is not only equivalent but better than the existing gasoline/Diesel infrastructure is critical to accelerate electric vehicle adoption.
The “4 C’s of charging” (coverage, capacity, convenience, and cost) is an essential focus when developing strategies to deploy charging infrastructure. Unlike the gas station model of conventional ICE vehicles that we have been accustomed to for many decades, electric vehicle charging offers a far greater variety of charging options. These different charging scenarios are characterized by different charging speeds, costs, and locations.

The common terms for *charging speeds* for the light duty electric vehicles that most U.S. drivers use are:

- Level1 charging: 120Vac, ~1.44kW (kilowatt), lowest cost
- Level2 charging: 240Vac, ~3.6kW to 19.2kW
- Level3 charging or “DC-Fast Charging”: 400Vdc to 800Vdc, ~50kW to 350kW, highest cost

The common *locations* for light duty vehicle charging infrastructure are

- Single family residential
- Multifamily residential
- Workplace
- Public urban Level2/DC-FC (DC-Fast Charging)
- Public intercity DC-FC

For daily commuting, the driver can generally charge where they are going to naturally park during their daily routines, say at their home or workplace. While traveling on trips or if living in a multifamily residence they can charge at far faster DC-Fast Chargers (DCFC) that approach (but don’t quite yet match) the refueling speed of a gas pump.

The most attractive and dominate use case is a PEV that is typically driven in daily commuting and charged at a single-family home overnight. Over 80% of charging is typically performed at the driver's home. While PHEVs have smaller batteries and typically can be charged overnight with a 120Vac Level-1 charger plugged into the ubiquitous NEMA 5-15 receptacle that virtually all other home electrical devices plug into. A 240Vac Level-2 charging is typically installed for much faster charging of BEVs with larger batteries or for PHEV drivers who wish to electrify more of their miles.

Level1 charging is the lowest cost, easiest to install, and creates virtually no additional stress on the grid. The driver simply plugs their mobile EV charging cord into a common 120Vac wall outlet as they do a vacuum cleaner, floor light, TV or any other device in their home. While Level1 may charge a PHEV overnight comfortably, it may not meet a driver's need for charging a longer-range BEV with a substantially larger battery.

The number of multifamily residences with overnight Level1 or Level2 charging infrastructure in their parking lot or garage is growing but is still more limiting that the opportunity to install Level1/2 at a drivers' own single-family home. Other options for these drivers include charging at work or at a public urban Level2/DC-Fast Charger. Innovative urban DCFC locations are where the driver can park and plug-in their EV and then walk a short distance to shopping, dining, or entertainment for the 30-60 minutes it may take to fill their battery. An example of a convenient arrangement is when a driver could gain enough charge to last for a week of commuting (say 300 miles) in less than hour while they complete their weekly grocery shopping or dining out.

When traveling between cities, intercity DCFC can now generally provide up to an 80% charge in 30 minutes or less on the most capable long range BEVs and today's DC-Fast Chargers. DCFC equipment is most costly to deploy and thus is generally the highest cost per kWh of energy for the driver to charge their battery.

Many DCFC deployment plans target a max of 50 miles between intercity DCFC with a minimum of 4 bays for each station. On the most sophisticated DCFC stations and networks, the driver can have a trip refueling experience that can be superior to an ICE vehicle. The driver can program their trip into their vehicle navigation system that then calculates the DC-FC locations to stop at along the route, shows the cost per kWh at each station and the number of stations available in real time, and the amount of time to optimally charge at each DCFC. They can pull into the charging bay, plug in the vehicle, have the vehicle automatically bill their credit card, and leave the vehicle to have a coffee or meal, enjoy shopping, or take a needed break or invigorating walk.

The costs vary for each of these charging speeds and locations. Level1 chargers are generally provided free with the vehicle and simply plug into a common 120Vac wall outlet.

Level2 chargers can cost $400 to $3000 (insert references and latest data) to install at a home. Multifamily Level2 installations are somewhat higher in cost given they are meant to be more rugged, sometime involve trenching to install, and may need payment or authorization systems. (insert Karl Popham chart estimates). The cost to install and operate a DC-FC are substantially higher given a DCFC can provide charging rates that are over 240 times faster than a Level1 charger. Each DC-FC unit can be $50k to $100k plus have higher grid charges from the utility. The DC-FC business case is the most challenging to achieve profitability. Firms that deploy DC-

FC will tend to achieve sufficient profitability as they learn how to reduce the up-front capital installation costs, achieve higher asset utilization from more charging session sales, and become creative with co-selling other profitable products while drivers are charging.

There are multiple charging station networks being installed in Texas through local utilities, auto manufacturers such as Tesla, and charging network companies such as evGO and ElectrifyAmerica. In addition, the Texas department of transportation (TxDOT) has a multi-year plan to develop a charging network with NEVI funding to enable drivers to travel across the state and spur economic development (https://txdot.mysocialpinpoint.com/tx_ev_plan). This plan intends to first install 4-bay DC-FC along all the major intercity alternative fuel corridors in Texas with a maximum of 50 miles spacing between stations within 1 mile from the interstate highway exit (Figure 1). Each of these stations will have a minimum of four 150kW chargers. Later, TxDOT will work with rural counties and cities to install DC-FC at or near the county seats across each of the remaining 254 Texas counties (Figure 2).

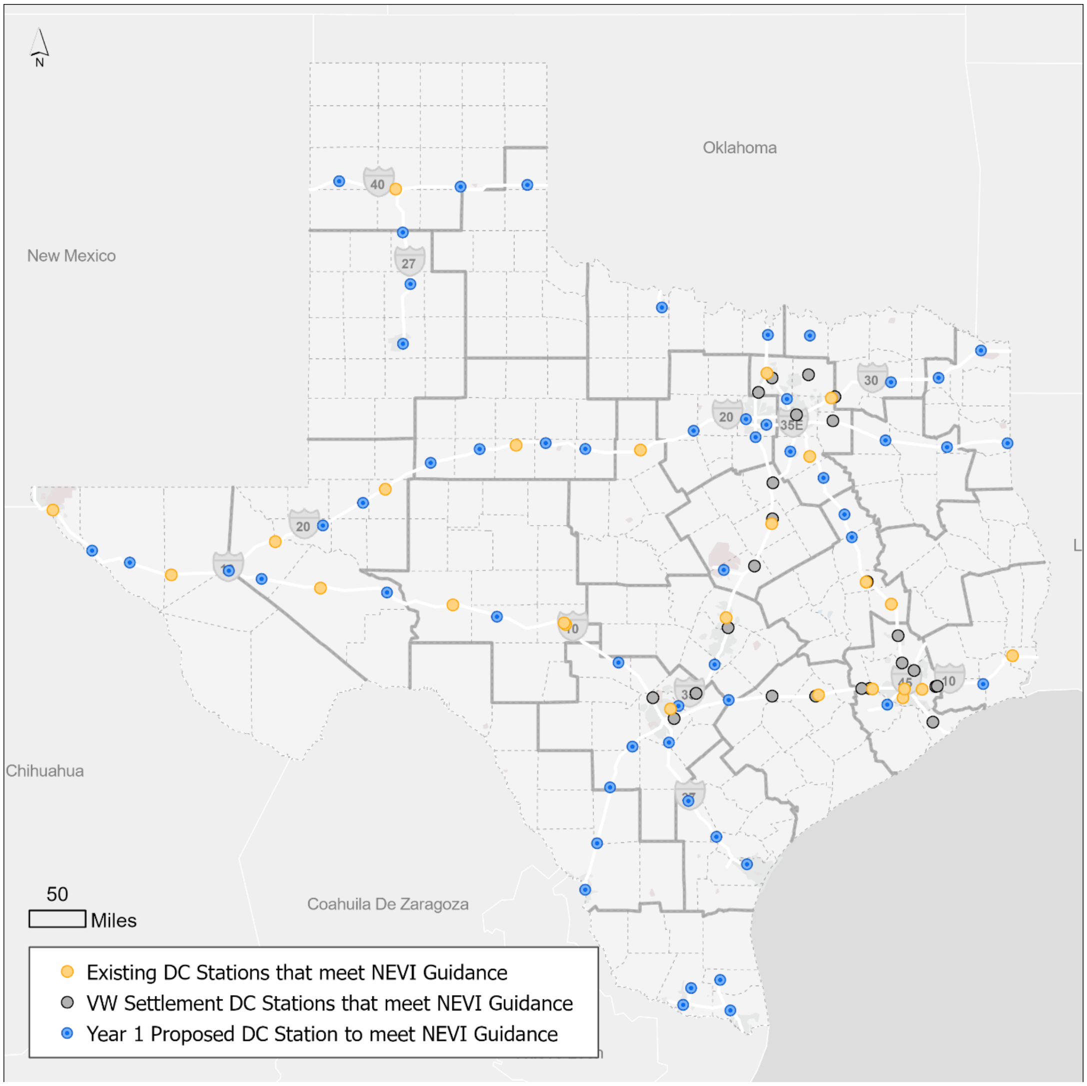


Figure 1: Proposed Electric Alternative Fuel Corridor DC-FC station placement (Source TxDOT)

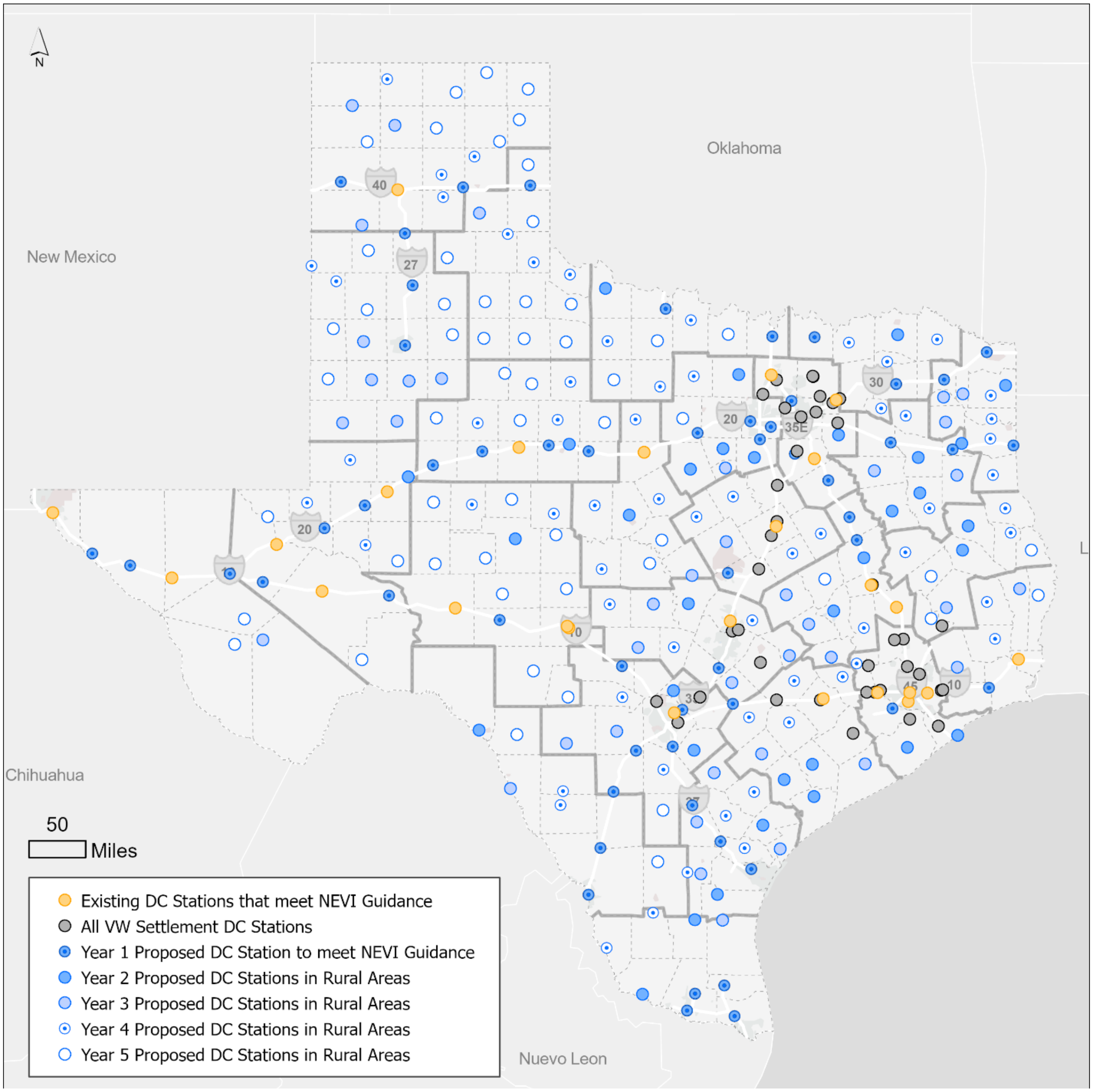


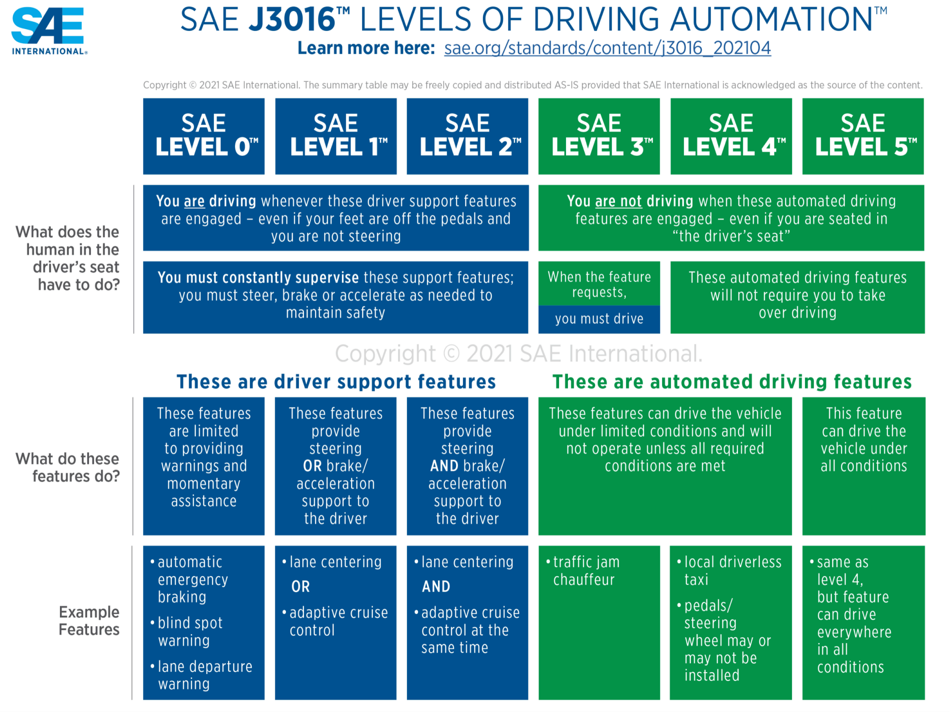
Figure 2: Statewide Coverage of Corridor & County Seat DCFC (Source TxDOT)

Autonomous Vehicles

Self-driving or autonomous vehicles are an exciting development that can provide new options to those who are traditionally mobility challenged, extend the years of mobility freedom, and reduce transportation costs or real estate used for parking. There is some debate whether autonomous vehicles will reduce overall traffic, congestion, and emissions.

The sensors, control hardware and software, and controls have substantially advanced since the pioneering days of the DARPA Grand Challenge and Urban Challenge (2004-2007) competitions that were created to nurture self-driving technology. Even with these advancements, fully self-driving vehicles on all roadways and conditions are not yet available to the average consumer or fleet.

Today, competitors are using different sensor suites with different combinations of cameras, sonar, radar, and LIDAR as well as varied hardware accelerators and software algorithms in pursuit of ever higher levels of functionality. While none have achieved SAE Level-5 autonomy capabilities (Figure 3, SAE Levels 0-5, https://www.sae.org/blog/sae-j3016-update) the technology is continuing to improve.



SAE **J3016**™ LEVELS OF DRIVING AUTOMATION™

Learn more here: sae.org/standards/content/j3016_202104

	SAE LEVEL 0™	SAE LEVEL 1™	SAE LEVEL 2™	SAE LEVEL 3™	SAE LEVEL 4™	SAE LEVEL 5™
What does the human in the driver's seat have to do?	**You are driving** whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			**You are not driving** when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	
	These are driver support features			**These are automated driving features**		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering **OR** brake/acceleration support to the driver	These features provide steering **AND** brake/acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	• automatic emergency braking • blind spot warning • lane departure warning	• lane centering **OR** • adaptive cruise control	• lane centering **AND** • adaptive cruise control at the same time	• traffic jam chauffeur	• local driverless taxi • pedals/steering wheel may or may not be installed	• same as level 4, but feature can drive everywhere in all conditions

Figure 3: SAE Levels of Driving Automation (Source SAE International)

Much of the value in the related technology is being delivered in products today in the form of ADAS (Automated Driver Assistance Systems) with features such as automatic emergency braking, lane-keep assist, or adaptive cruise control. While not providing full autonomy, these features can help reduce injuries and fatalities while the self-driving technology progresses further.

The sensor, computing, and servo control of self-driving technology can create a meaningful additional load for the electrical system of a vehicle. Electric and electrified vehicles (BEV, PHEV, HEV, and H2FCV) have an advantage over conventional vehicles in supporting this extra electrical load given their considerable battery and power electronics capabilities. That said, autonomous technologies can also be incorporated in conventional ICE vehicles but at additional cost and complexity. Therefore, even though autonomous vehicle technology can sometimes get grouped together in categories such as CASE: Connected, Autonomous, Shared, Electric Vehicles, autonomous and electric vehicle technologies can be mostly be considered independent technologies.

We should expect to see continued improvements of the technology cost and capability over time. Some particular highest-value added market segments taking the lead in deployments. Improvements in safety, efficiency, and cost may lead commercial trucking or fleets to deploy the most advanced systems more rapidly.

Vehicles to Everything (V2X)

"V2X" is a generic term to describe a variety of vehicle to vehicle, infrastructure, load, home, grid interactions. The term V2X can have different definitions based upon context. When V2X includes V2V and V2I (Vehicle-to-Vehicle and Vehicle-to-Infrastructure) it generally implies communications (and not electric power flow0 that can improve safety, congestion, and traffic flow.

When V2X includes V2L, V2H, or V2G (Vehicle-to-Load, Vehicle-to-Home, Vehicle-to-Grid) it involves electrical power flowing to or from the vehicle. This bi-directional power-flow to an isolated load or microgrid with V2L or V2H or vehicle-grid interaction with V2G leverages the considerable battery, energy storage, or power output capability of a BEV, PHEV, or H2FCV (https://ieeexplore.ieee.org/iel5/5165411/6155182/06122479.pdf)

V2L

Vehicle-to-Load is a capability where the vehicle can provide power output to individual loads, such as power tools, pumps, fans, TVs, refrigerators, communications equipment. V2L allows the vehicle to act as a quieter, more convenient, and lower emissions backup generator. It may be manually connected to a home for rudimentary critical home load backup if the home is configured with an input box, transfer switch, and critical load breaker panel. The vehicle simply incorporates power conversion devices and common receptacles that allow these loads to plug into the vehicle as they would at a typical home. Two examples are a more simple, lower power 120Vac outlet in the rear of an SUV (Figure 4) and a more capable 120Vac plus 240Vac V2L option offered by Ford on their F150 Pickup (Figures 5, 6).

Figure 4: 120Vac outlet (source David Tuttle)

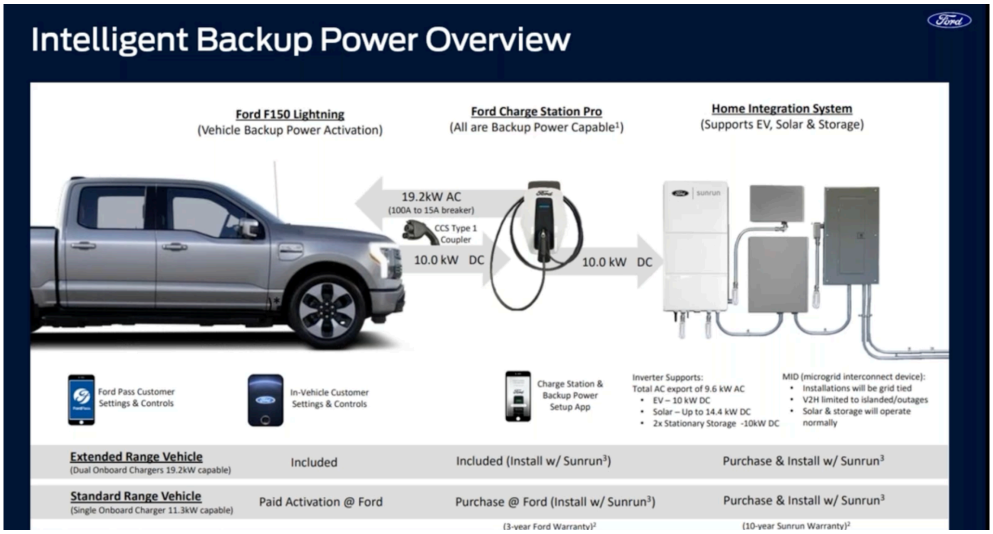
Figure 5: 120Vac and 240Vac receptacles (source Ford)

Figure 6: Powering Loads with V2L (source Ford)

V2H

Vehicle-to-Home is a capability where the vehicle can provide more seamless and automatic power to back-up a home when the grid fails. The vehicle is charged and discharged through the power cord that is typically used to charge the PEV.

One of the first examples offered is named “Intelligent Backup Power” that uses an off-vehicle DC-AC inverter, transfer switch, dark-start battery, and bi-directionally capable EVSE (electric vehicle supply equipment, or charger). The system senses when the grid fails and then automatically reconfigures the system to output power from the vehicle’s battery, PHEV range extender, or Hydrogen fuel cell to power the home. The transfer switch isolates the home from the grid which is essential to safely create a microgrid that can be powered by the vehicle. Once the grid is functional again, this IBP system switches back to the grid and disables power export from the vehicle. (Figures 7,8)



Intelligent Backup Power Overview

	Ford F150 Lightning (Vehicle Backup Power Activation)	**Ford Charge Station Pro** (All are Backup Power Capable[1])	**Home Integration System** (Supports EV, Solar & Storage)
	Ford Pass Customer Settings & Controls In-Vehicle Customer Settings & Controls	Charge Station & Backup Power Setup App	Inverter Supports: Total AC export of 9.6 kW AC • EV – 10 kW DC • Solar – Up to 14.4 kW DC • 2x Stationary Storage -10kW DC MID (microgrid interconnect device): • Installations will be grid tied • V2H limited to islanded/outages • Solar & storage will operate normally
Extended Range Vehicle (Dual Onboard Chargers 19.2kW capable)	Included	Included (Install w/ Sunrun[3])	Purchase & Install w/ Sunrun[3]
Standard Range Vehicle (Single Onboard Charger 11.3kW capable)	Paid Activation @ Ford	Purchase @ Ford (Install w/ Sunrun[3]) (3-year Ford Warranty)[2]	Purchase & Install w/ Sunrun[3] (10-year Sunrun Warranty)[2]

Figure 7: Intelligent Backup Power (source Ford)

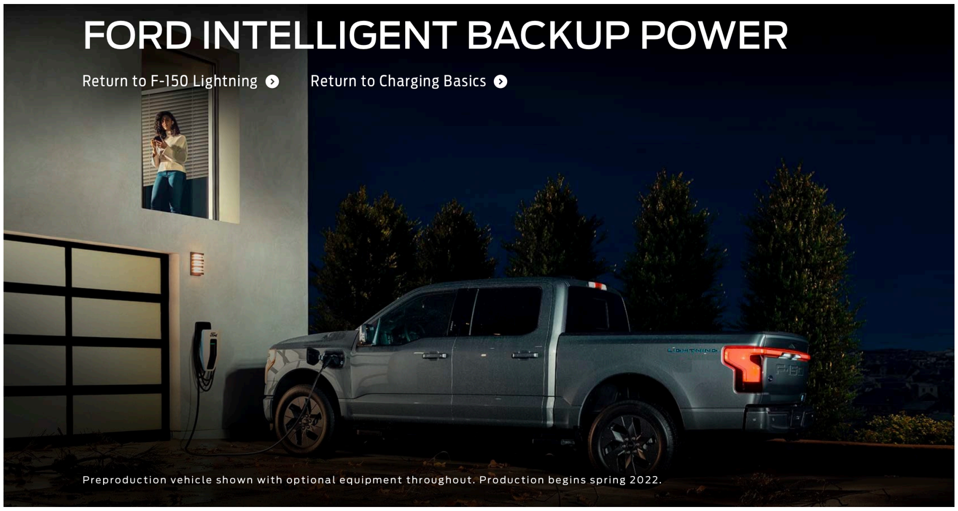


Figure 8: Intelligent Backup Power Bi-directional charging (source Ford)

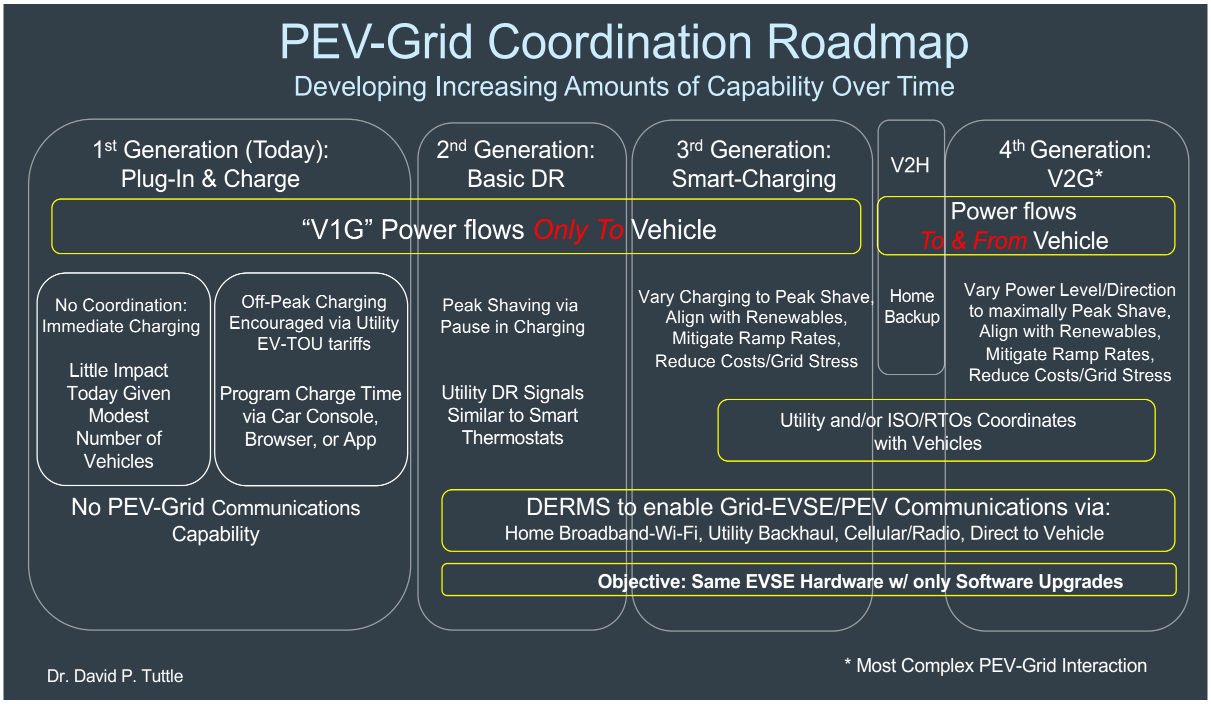
V2G

Vehicle-to-Grid uses the electric vehicle's battery to provide services to reduce grid costs, stress, or emissions in return for compensation for the vehicle owner.

The vehicle is charged or discharged through the power cord that is typically used to charge the PEV. While a dedicated V2G system without a transfer switch cannot provide power to back-up a home when the grid fails as a V2H system can, a V2G system can leverage a potentially huge pool of storage in the electric vehicle fleet. A rough estimate is that for every 1M new PEVs on the road, a pool of 75GWh of storage could be tapped as a huge lower-cost flexible distributed energy resource (DER). V2G as a concept has been explored for a number of years however, the number of electric vehicles on the road is only recently becoming significant enough to attract investment deployment beyond pilots. While the vehicle storage is already

purchased as part of the vehicle, other factors such as the cost and lack of availability of bi-directional charging infrastructure, challenges with utility SCADA/back-office software integration, immaturity of common industry standards, and EV manufacturers' concern over battery degradation have been meaningful impediments to broader scale deployment.
The exciting promise of V2G is the ability to have electric vehicle charging and discharging be very synergistic with the grid. Intelligent charging of the vehicle could be deployed when electricity prices, emissions, or stress are low. Opportunistic discharging could further reduce the grid's peak demand, help mitigate ramp rates from increasing amounts of renewable generation, and reduce electricity costs for both EV and non-EV drivers.

Utilities, auto and charging equipment manufacturers, and customers will likely not jump from first charging their EV with only rudimentary levels of sophistication to V2G. V2G is the most sophisticated form of vehicle-grid interaction. There likely will a progression of steps that make EV charging more intelligent, then enabling bi-directional power charging, and then V2H/V2G. Figure 9 provides one vision of this progression of Vehicle-Grid-Integration (VGI) that includes V1G intelligent charging and V2G.



PEV-Grid Coordination Roadmap

Developing Increasing Amounts of Capability Over Time

1st Generation (Today): Plug-In & Charge

2nd Generation: Basic DR

3rd Generation: Smart-Charging

V2H

4th Generation: V2G*

"V1G" Power flows *Only To* Vehicle

Power flows *To & From* Vehicle

No Coordination: Immediate Charging

Little Impact Today Given Modest Number of Vehicles

Off-Peak Charging Encouraged via Utility EV-TOU tariffs

Program Charge Time via Car Console, Browser, or App

No PEV-Grid Communications Capability

Peak Shaving via Pause in Charging

Utility DR Signals Similar to Smart Thermostats

Vary Charging to Peak Shave, Align with Renewables, Mitigate Ramp Rates, Reduce Costs/Grid Stress

Home Backup

Vary Power Level/Direction to maximally Peak Shave, Align with Renewables, Mitigate Ramp Rates, Reduce Costs/Grid Stress

Utility and/or ISO/RTOs Coordinates with Vehicles

DERMS to enable Grid-EVSE/PEV Communications via:
Home Broadband-Wi-Fi, Utility Backhaul, Cellular/Radio, Direct to Vehicle

Objective: Same EVSE Hardware w/ only Software Upgrades

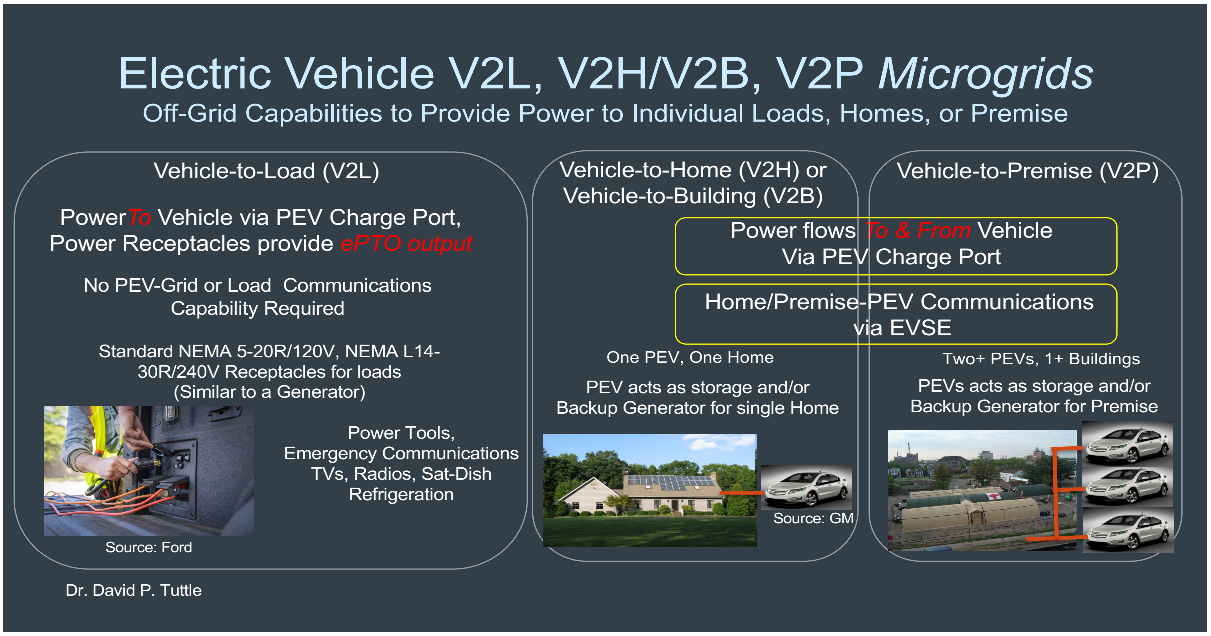
Dr. David P. Tuttle

* Most Complex PEV-Grid Interaction

Figure 9: PEV-Grid Integration Roadmap

In addition, customers may find great value in vehicle power export (VPE) with V2L and V2H. Note that some also may use the terminology V2B (vehicle-to-building). In this paper, the author is differentiating when the vehicle is engaged with the grid with V1G (e.g. Intelligent charging) or V2G and then when the vehicle and home/loads are isolated from the grid with V2L or V2H.

With vehicle power export, individual loads in remote areas, camping or tailgating, or emergency command centers can be powered with a more convenient, quiet, and lower emissions fashion than with traditional portable or standby generator. Figure 10 shows a vision for VPE.



Electric Vehicle V2L, V2H/V2B, V2P *Microgrids*

Off-Grid Capabilities to Provide Power to Individual Loads, Homes, or Premise

Vehicle-to-Load (V2L)

Power To Vehicle via PEV Charge Port,
Power Receptacles provide ePTO output

No PEV-Grid or Load Communications
Capability Required

Standard NEMA 5-20R/120V, NEMA L14-30R/240V Receptacles for loads
(Similar to a Generator)

Power Tools,
Emergency Communications
TVs, Radios, Sat-Dish
Refrigeration

Source: Ford

Vehicle-to-Home (V2H) or
Vehicle-to-Building (V2B)

Vehicle-to-Premise (V2P)

Power flows To & From Vehicle
Via PEV Charge Port

Home/Premise-PEV Communications
via EVSE

One PEV, One Home

PEV acts as storage and/or
Backup Generator for single Home

Source: GM

Two+ PEVs, 1+ Buildings

PEVs acts as storage and/or
Backup Generator for Premise

Dr. David P. Tuttle

Figure 10: Vehicle Power Export Roadmap