Vehicles-to-Grid Integration Assessment Report

January 2025

United States Department of Energy
Washington, DC 20585

Executive Summary

The Department of Energy (DOE) established a program for the integration of electric vehicles (EVs) onto the electric grid and to conduct and report on an Assessment Study of Vehicle Grid Integration (VGI). This report has been prepared to provide the results of the study that the Department conducted, as well as a 10-year roadmap for the VGI Program at the DOE, including the establishment of the DOE VGI Initiative.

The VGI Initiative will advance capabilities necessary for the United States to cohesively accomplish transportation electrification, grid modernization, renewable energy resources integration, climate change mitigation and adaptation, enhance energy security and resilience, and ensure equitable access to all of the benefits of electric transportation. The goal of integrating EVs onto the electric grid is to harmonize the EVs' transportation mission with the U.S. electric infrastructure mission, fulfilling societal and environmental obligations.

The transportation sector and electric grid represent the backbone of the U.S. economy and way of life. While each has evolved independently, the transition to EVs will require the coupling of these two sectors. This coupling must be based on the intelligent integration of EVs with the electric grid, referred to as VGI. VGI can enable foundational changes across the transportation and electric sectors, with vehicles no longer just being a tool of the movement of people and goods. VGI allows EVs to be a highly controllable load and mobile storage device capable of performing advanced grid services that provide value to vehicle owners, expanded operational capabilities for grid operators, and new markets for aggregation of these EV services.

The electrification of the transportation sector is accelerating, with 1.2 million EVs sold in the United States during 2023, which represents more than 8% of new light duty vehicle sales. Nearly all vehicle manufacturers are now, or soon will be, selling EVs, and several have announced plans to shift all their models offered to electric within the next 10-15 years. These plans, in conjunction with state level requirements for EV sales, will result in tens of millions of EVs on U.S. roads in the next 10 years.

The primary mission of the electricity grid is to reliably provide electricity to end users. The grid has always adapted to meet increases in electricity use created by the introduction of new technologies, e.g., air conditioning, and it will do the same for the potentially large increase in loads created by the electrification of the on-road transportation sector. Transportation electrification is happening at a time of several other influences on the grid such as distributed solar, energy storage, responsive buildings, and increased needs for resilience. The modernization of the grid, coupled with VGI, is essential to providing nationwide and equitable access to EVs. Without both modernization and VGI, the increased loads on the grid at the distribution and transmission levels could result in grid reliability and resilience problems, especially in rural and underserved communities.

VGI represents a multifaceted problem because of the mix of entities involved as depicted in Figure 0.1. When done properly, VGI has potentially significant resilience, reliability, and economic benefits to the country. Appropriately planned and implemented VGI will benefit all electricity consumers, including individuals and businesses, not only grid operators and EV owners.

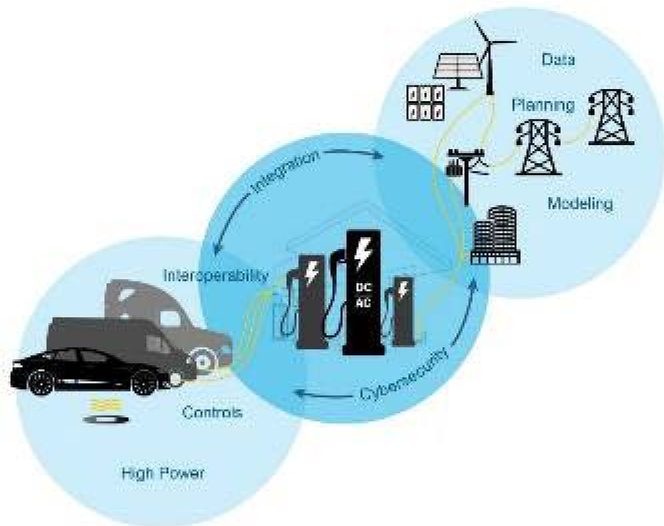

Figure 0.1. VGI Ecosystem.

EVs are not like typical loads on the grid. Since they typically are connected to the grid for long periods of time and the time when and rate at which they are charged is controllable, they can provide a wide range of grid services, such as peak shaving, load shifting, and demand response. Providing grid services by controlling charge is referred to as V1G. Since EVs also have large batteries, ranging from tens to hundreds of kWh, they also have the potential to be mobile power export devices, referred to by industry as V2X, not to be confused with the use of the same acronym regarding autonomous vehicle communications. V2X capable EVs could provide power to homes (V2H), buildings (V2B), and the grid (V2G). This would allow V2X capable EVs to provide even greater grid services such as back-up power in emergencies and potential assistance to black start operations which requires generation assets to be brought on-line to restart parts of the grid in a coordinated approach to recover from a black-out.

EVs providing grid services can not only help support grid resilience and reliability, but they can also help defer the need for grid infrastructure upgrades. Realizing these benefits will require proper VGI to be implemented. Stakeholders in the transportation and electricity sectors will need to collaborate, share information, and address techno-economic challenges, codes and standards issues, and cybersecurity concerns. These challenges span the entire EV charging ecosystem, including the EV, the Electric Vehicle Supply Equipment (EVSE) or charger, and the distribution, transmission, and generation systems of the grid. Overcoming these challenges and aligning all the pieces of the ecosystem to be fully integrated will require a significant body of work, but the benefits to the country are undeniably worth the effort.

The Department is conducting research for specific aspects of VGI covering impacts on EVs and the grid, grid services, codes and standards, and cybersecurity for this report. The VGI study was based on the work performed and being conducted across the DOE complex, consultations with National Institute of Standards and Technology (NIST), review of reports and studies by non-DOE researchers and VGI stakeholders, and input received directly from stakeholders. The report contains takeaways and recommendations from the study, which are presented in detail in each subsection of Section II Study Results and in a summary table in Section III Recommendations. The recommendations were developed by DOE to address the challenges and issues associated with VGI.

DOE has been conducting Research, Development, Demonstration, and Deployment (RDD&D) activities related to integration of EVs with the grid for years, and as the transportation and grid sectors have evolved, these efforts have been increasingly coordinated. DOE has developed a 10-year roadmap of the DOE VGI RDD&D Program to implement the recommendations in this report and to address the VGI challenges and issues that fall within the purview of DOE. This roadmap, found in Section III.B of the report, details how the DOE VGI Initiative, comprised of a cross-Departmental team, will lead RDD&D efforts that integrate vehicles onto the grid to achieve decarbonization, cost-effectiveness, resilience, and reliability goals.

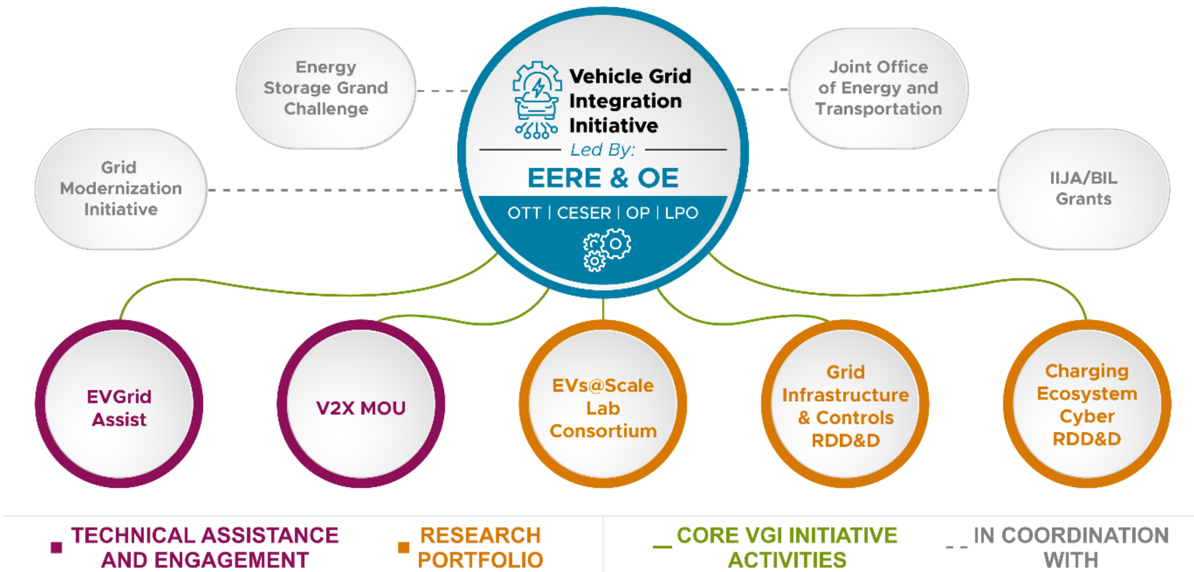

Figure 0.2. DOE VGI Initiative Participants and Focus Areas

The work will include efforts on smart and bi-directional charge management, high-power charging (HPC), grid operations and controls, codes and standards, and cybersecurity, in a coordinated, cooperative manner. This team, led by the Office of Energy Efficiency and Renewable Energy (EERE), and the Office of Electricity (OE), and including the Office of Technology Transitions (OTT), the Office of Cybersecurity, Energy Security, and Emergency Response (CESER), and the Office of Policy (OP), conducted the VGI study detailed in this report and developed the DOE VGI Roadmap to ensure that activities across all offices are properly coordinated and all VGI challenges and issues are appropriately addressed. The DOE team will work with other Federal Agencies and a broad spectrum of stakeholders to implement the VGI Program.

VGI is critical to the electrification of the transportation sector and the modernization of the electric grid. While the cross-sectoral challenges to VGI are sizeable, they can be overcome and DOE is prepared to conduct the RDD&D needed to establish U.S. leadership in VGI, create good paying U.S. jobs, and contribute to combating climate change.

VEHICLES-TO-GRID INTEGRATION ASSESSMENT REPORT

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I. Background

Mobility is key for America's economy: annually, vehicles transport 18 billion tons of freight—about $56 billion worth of goods each day[1]—and currently move people more than 3 trillion vehicle-miles per year[2]. The transportation sector accounts for approximately 30% of total U.S. energy needs[3] (Figure I.1), and, because of historical reliance on petroleum, which supports over 90% of the transportation energy today[4], transportation recently surpassed electricity generation to become the largest source of carbon dioxide emissions in the country[5]. Vehicle electrification offers a technology pathway for continuing to move America's people and goods with lower greenhouse gas (GHG) emissions, improved air quality, and reduced reliance on foreign petroleum, as well as opportunities to improve health and alleviate inequities.

[1] Bureau of Transportation Statistics, DOT, Transportation Statistics Annual Report 2020, Table 4-1. https://www.bts.gov/tsar.

[2] Transportation Energy Data Book 39th Edition, ORNL, 2021. Table 3.9 Shares of Highway Vehicle-Miles Traveled by Vehicle Type, 1970-2019.

[3] Transportation Energy Data Book 39th Edition, ORNL, 2021. Table 2.2. U.S. Consumption of Total Energy by End-use Sector, 1950-2018.

[4] Transportation Energy Data Book 39th Edition, ORNL, 2021. Table 2.3 Distribution of Energy Consumption by Source and Sector, 1973 and 2019.

[5] Environmental Protection Agency, Draft U.S. Inventory of Greenhouse Gas Emissions and Sinks, 1990-2019, Table 2-11. Electric Power-Related Greenhouse Gas Emissions and Table 2-13. Transportation-Related Greenhouse Gas Emissions.

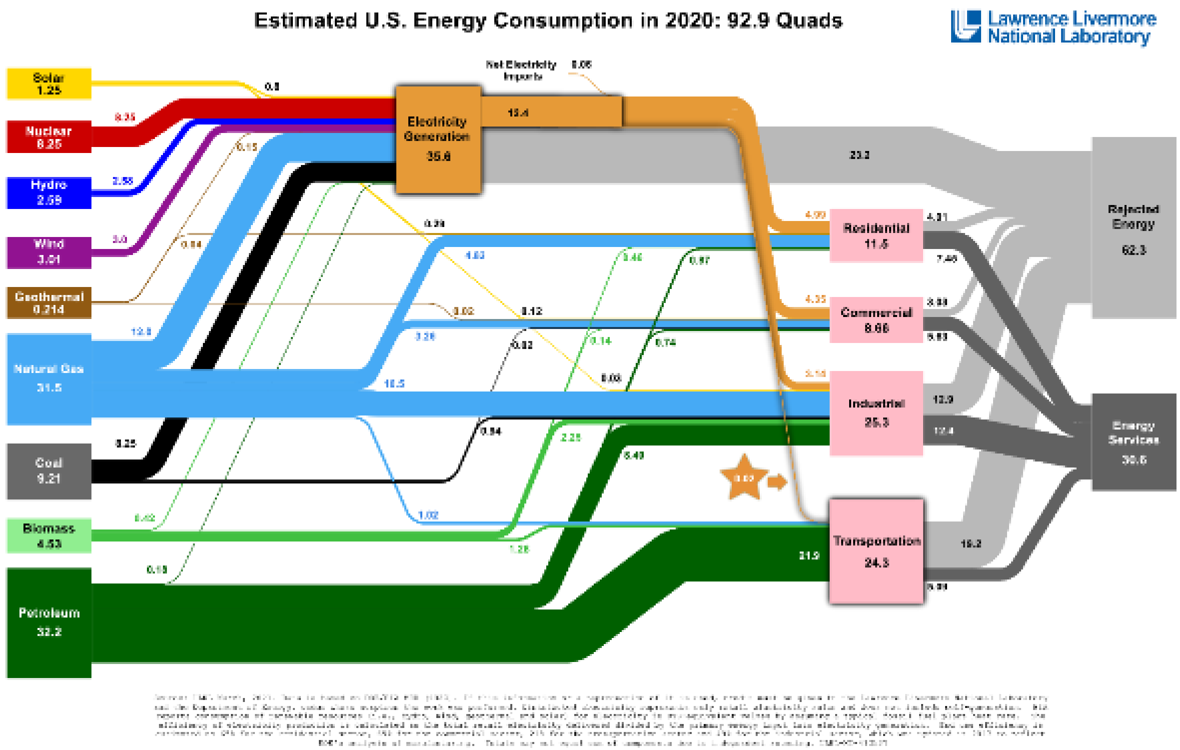

Figure I.3. U.S. Energy Flows.

In Figure I.1, the orange star indicates current level of energy interdependency between the electric sector and the transportation sector[6].

The figure above also highlights how little electricity is used for motive power in vehicles in the transportation sector today. As of 2020, the transportation sector was 90% dependent on petroleum, 5% on biomass, 4% on natural gas, and slightly under 1% on electricity. It could be said that the electric and transportation sectors are only *weakly coupled,* with few interdependencies. By comparison, the residential and commercial sectors were both approximately 50% dependent on electricity, and are therefore *strongly coupled*, with extensive interdependencies. For over 100 years, the residential and commercial sectors have influenced the design and operation of the electric sector, while the transportation sector has not. Transportation electrification will elevate the importance of transportation electricity use and may require a reassessment of how the grid is designed and operated. Integrating electric vehicles onto the grid is a transformational activity. Strong sector coupling will require a different scale of analysis with emphasis on the big picture and the long term, both because of the extent of the interdependencies and the time needed to alter the structures of the electric grid.

As shown in Figure I.2, integrating EVs onto the electric grid enables reductions in the total energy consumed by the U.S. transportation sector because EVs using grid sourced energy are more energy efficient than conventional vehicles that use petroleum fuels. The figure shows

[6] Lawrence Livermore National Laboratory (emphasis added).

that the higher the level of EV adoption the greater will be the reduction in total energy consumption by the transportation sector.

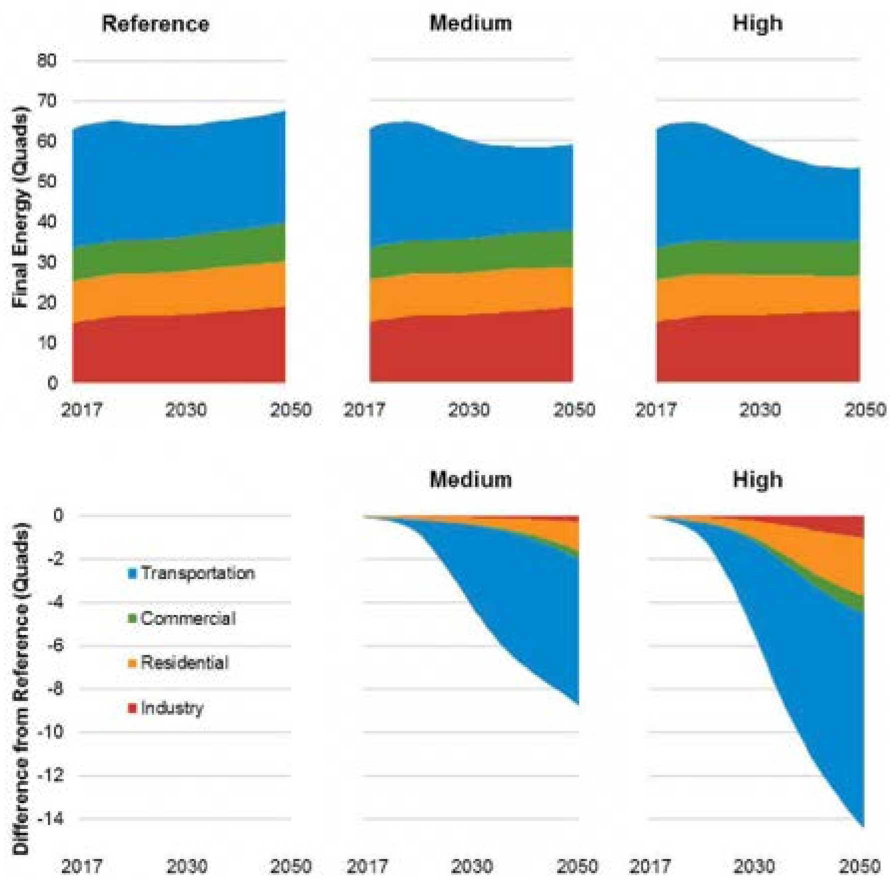

Figure I.4. Future Energy Consumption Scenarios -Total Energy Consumption estimates for Reference, Medium, and High EV adoption scenarios; Source: NREL Electrification Futures Study (Mai, 2018)[7].

To identify the requirements for establishing an RDD&D program to integrate EVs onto the electric grid, it is useful to understand the likely scope of future penetration of EVs in the U.S. transportation sector and the basics of the current systems (e.g., EVs, grid, and charging equipment) that must evolve to fully integrate EVs onto the electric grid. This background section will present predictions on the scope of future transportation electrification (Section I.A), the fundamentals of how the electric grid operates (Section I.B), the current state of EVs and charging technologies (Section I.C), and the inherent coupling of future U.S. transportation and the electricity sectors (Section I.D).

[7] Mai, Trieu, Paige Jadun, Jeffrey Logan, Colin McMillan, Matteo Muratori, Daniel Steinberg, Laura Vimmerstedt, Ryan Jones, Benjamin Haley, and Brent Nelson. 2018. Electrification Futures Study: Scenarios of Electric Technology

A. The U.S. Transportation Sector and Electric Vehicle Future Potential

Current Market Trends and Consumer Adoption

The modern EV was introduced to the U.S. market in December 2010, with the advent of GM's plug-in hybrid electric Chevrolet Volt and Nissan's all-electric LEAF. In the decade since, the number of PEV[8] makes and models available to U.S. consumers has expanded – increasing from 2 vehicle models to nearly 50 vehicle models; as Figure I.3 shows, PEV sales increased from one-hundred thousand in 2015 to 1.2 million by 2023.

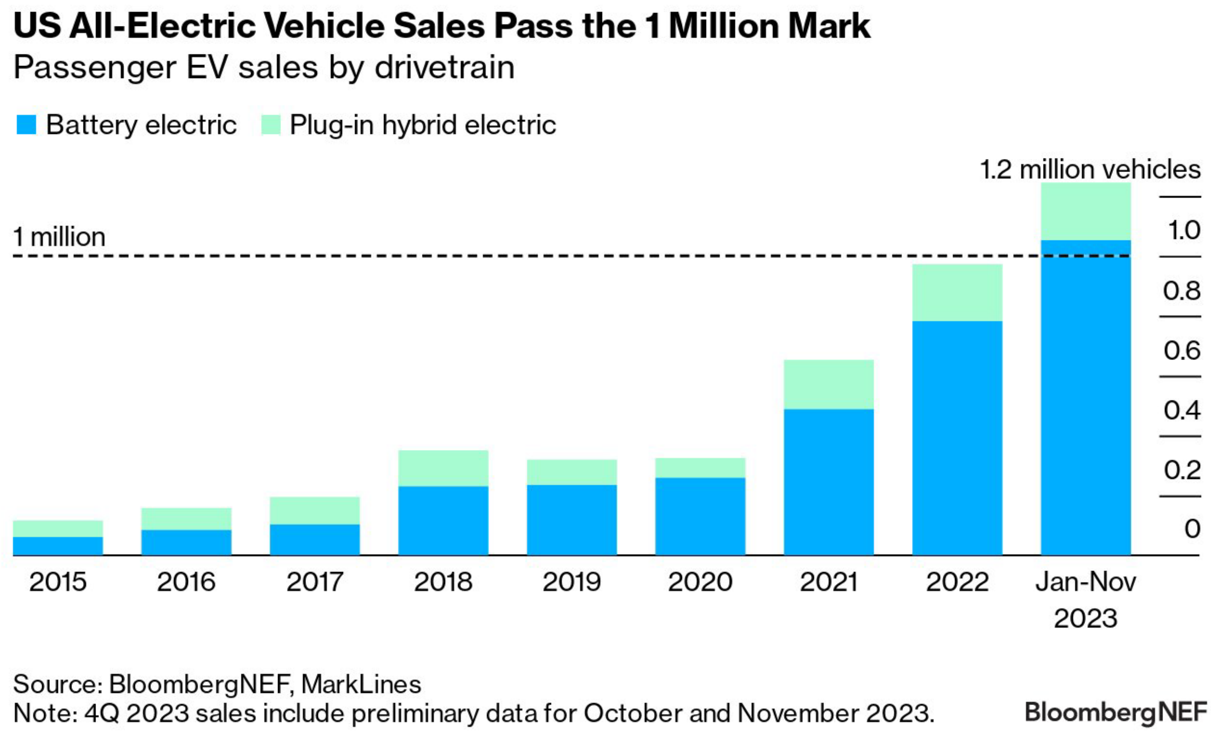

Figure I.5. Sales of new light-duty EVs in the U.S. over time by technology. Annual sales of PEVs increased from one-hundred thousand in 2015 to over 1.2 million by 2023; over 4 million new EVs have been sold in the U.S. in the past decade. By October 2023 PEVs had more than an 8% share of all U.S. light duty vehicle (LDV) sales[9]. Source of Graphic: BloombergNEF, MarkLines[10].

In addition to lower tailpipe GHG and air pollutant emissions, EVs offer American consumers economic benefits: since EVs are more energy-efficient, annual fuel expenditures can be 20–90%

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[8] Plug-in Electric Vehicles (PEVs) include Battery-Electric Vehicles (BEVs) and Plug-in Hybrid-Electric Vehicles (PHEVs).

[9] Source data can be found at https://www.anl.gov/es/light-duty-electric-drive-vehicles-monthly-sales-updates and https://publications.anl.gov/anlpubs/2022/11/178584.pdf.

[10] Levin, Tim. Inside EVs. *What Slowdown? America Crosses The 1 Million EVs Sold Mark In 2023.* Dec. 5, 2023. [online]: https://insideevs.com/news/699463/us-ev-sales-1-million/. Accessed Dec.7, 2023.

lower than those for a comparable gasoline vehicle[11], which is critically important when the transportation sector accounts for over 15% of average U.S. household expenditures[12]. Maintenance costs of EVs are typically lower than those of comparable gasoline vehicles, too, since EVs have fewer moving parts. Broadly, environmental impacts are dependent on grid generation resources.

Even so, barriers to EV adoption remain, including a relatively high up-front purchase price, the (historically) limited number of vehicle models available, a combination of limited driving range and a growing but still-limited charging infrastructure, and other less tangible challenges such as general consumer skepticism towards new technology. EV purchase prices have declined rapidly over the past decade, thanks largely to lithium-ion battery pack cost reductions of over 80% (from over $1,000/kWh in 2008 to $132/kWh at the end of 2021[13]). EV range and charging station availability also continue to grow, with average new EV range growing to almost 300 miles (compared to only 70 in 2008)[14] and nearly 60,000 public charging stations are currently available in the United States[15]. Although most EV users currently have access to and rely on at-home charging, public charging infrastructure is still limited, with roughly one public charge point per 10 EVs[16]. Continued growth in EV charging infrastructure will offer multiple benefits: increased consumer confidence, charging access for those without the ability to plug-in at home, and exposure for a greater portion of America's driving public to EV technologies.

While growth in the EV market for medium- and heavy-duty vehicle (MDV and HDV) modes has lagged that of the light-duty vehicle (LDV) sector, there are several companies that are adopting EVs into their delivery fleets. The factors influencing the slower growth of M/HDVs include challenges posed by the need for larger batteries and associated costs, weights, and recharging times. Growth of the electrification of M/HDVs has been influenced by the heterogeneous composition of the market where economies of scale may not come quite as easily, and the premium placed on space and weight in the freight sector[17]. (Future market trends are discussed in Section I.A.v.)

Climate Change, Environmental Quality, and Fuel Security

Transportation electrification presents an opportunity to slow and potentially lessen the impact of climate change, to reduce both GHG and criteria air pollutant emissions and to diversify transportation fuels away from imported petroleum to domestically-produced primary energy

[11] U.S. DOE (2021). Transportation Fact of the Week. All-Electric Vehicles Have the Lowest Estimated Annual Fuel Cost of All Light-Duty Vehicles. https://www.energy.gov/eere/vehicles/articles/fotw-1179-march-29-2021-all-electric-vehicles-have-lowest-estimated-annual

[12] Transportation Energy Data Book 39th Edition, ORNL, 2021. Table 11.1 Average Annual Expenditures of Households by Income, 2019.

[13] BloombergNEF 2022.

[14] Gohlke, David, Zhou, Yan, Wu, Xinyi, and Courtney, Calista. *Assessment of Light-Duty Plug-in Electric Vehicles in the United States, 2010 – 2021*. https://publications.anl.gov/anlpubs/2022/11/178584.pdf

[15] Alternative Fuels Data Center (2022). Electric Vehicle Charging Station Locator. https://afdc.energy.gov/stations/#/analyze?country=US&fuel=ELEC

[16] Muratori et al. (2021). The rise of electric vehicles—2020 status and future expectations. Prog. Energy (3) 022002.

[17] Domonske, C. (2021). From Amazon To FedEx, The Delivery Truck Is Going Electric. NPR. https://www.npr.org/2021/03/17/976152350/from-amazon-to-fedex-the-delivery-truck-is-going-electric

sources for electricity generation. As Figure I.4 depicts, even when expressed on a well-to-wheels lifecycle basis that accounts for "upstream" emissions associated with electricity generation and fuel production, EV technologies powered by today's average U.S. grid produce more than 60% lower GHG emissions, more than 30% lower fine particulate matter emissions, and nearly 100% lower petroleum consumption than a comparable internal combustion engine vehicle (ICEV). The magnitude of these emissions reductions can depend on the grid generation mix. For a grid powered entirely by natural gas (combined cycle), fine particulate emissions are even lower; if powered by renewables, GHG and particulate emissions are both lower still; and in a hypothetical case where an EV is powered entirely by coal-fired electricity, GHG emissions are still lower than a comparable ICEV. In all cases, EVs improve transportation fuel security by hedging almost entirely against price and geopolitical uncertainties, replacing the need for imported oil with the use of domestic grid resources. Figure I.4 expresses emissions and petroleum outcomes on a per-mile basis for light-duty vehicles, such that results are generally proportional for medium- and heavy-duty vehicles on a per-mile or per-ton-mile basis.

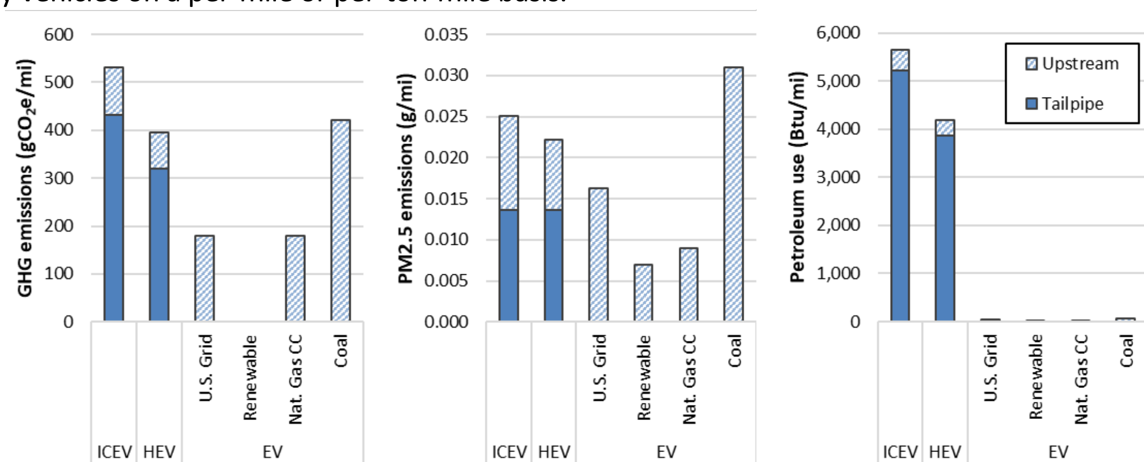


Figure I.6. A comparison of well-to-wheel lifecycle greenhouse gas (GHG) emissions (left), fine particulate matter (PM2.5) emissions, and petroleum use for several representative average U.S. Model Year 2019 mid-size vehicles that differ only by powertrains: an internal combustion engine vehicle (ICEV) running on average gasoline, a hybrid electric vehicle (HEV, i.e., that does not plug in[18]) running on average gasoline, and an electric vehicle (EV) powered by the average U.S. grid, with sensitivities shown for a grid powered entirely by renewables, natural gas (combined cycle), or coal. Emissions are calculated using Argonne National Laboratory's GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model) model 1 [19], version 2020.

EV Market Policy Context

In recent decades, U.S. Federal policies toward EVs have involved a combination of three primary approaches: technology investment, direct subsidies, and regulatory policy. In FY21, the Department of Energy's Vehicle Technologies Office invested $178.7 million in battery and electric-drive technology R&D. Federally supported R&D programs reduced the cost of lithium-ion battery packs from over $1,000/kWh in 2008 to $132/kWh at the end of 2021[13]. Additionally, starting in

[18] The analysis assumed "Full Hybrid" capabilities for the HEVs where the vehicles can run only on the combustion engine, only on the electric motor, or a combination of both.

[19] GREET WTW Calculator and Sample Results from GREET 1 2020. https://greet.es.anl.gov/index.php?content=sampleresults

2010, U.S. purchasers of light-duty EVs qualified for a Federal tax credit[20] of up to $7,500 (depending on the battery capacity of the EV purchased, and additional incentives may have been available by state, as described below) for the first 200,000 vehicles sold by manufacturer (Tesla and General Motors surpassed this threshold in 2019 and 2020, respectively). EV tax credits for new vehicle purchases during the period from 2023 to 2032 are in the process of being updated as required by the Inflation Reduction Act (IRA)[21]. EVs are also supported by—and support vehicle manufacturer compliance with—two coordinated Federal regulatory policies for Passenger Cars and Trucks: the U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) Corporate Average Fuel Economy (CAFE) standards and the U.S. Environmental Protection Agency's Regulations for Greenhouse Gas Emissions. The CAFE standards incentivize EVs, by applying the Petroleum Equivalency Factor (PEF) – a multiplier of approximately 6.6 to each EV's fuel economy in tabulating each vehicle manufacturer's annual corporate average for purposes of compliance[22]. The LDV GHG rule considers only tailpipe rather than well-to-wheel lifecycle emissions (see Figure I.4), thereby accounting for EVs as zero-emission vehicles.

Recent state and local EV market policies vary greatly, as Figure I.5 shows, and can include various combinations of financial incentives for the purchase of a vehicle itself, financial incentives for the purchase of equipment to charge an electric vehicle, time-of-use rates for EV charging, non-cost incentives that affect how EVs are used, and public vehicle purchase directives. U.S. states have administered EV purchase subsidies as grants, rebates, sales tax exemptions, and/or income tax credits; while some states offer vehicle registration fee exemptions, other states impose additional EV fees (since EVs are not affected by state motor fuel taxes). Programs are also in place for direct subsidies or other cash incentives to support the purchase and installation of EVSE (Electric Vehicle Supply Equipment, commonly known as "charging equipment" or a "charging station"), including for public and residential use, with special incentives in some states for EVSE installed at multifamily housing. Policies also affect the cost to charge in some states, with regulators granting electric utilities permission to lower the cost of electricity for EVs charging at off-peak hours (known as "time-of-use" (TOU) charging); still, other policies encourage EV purchases with high-occupancy vehicle (HOV) lane permissions, special parking privileges, or exemption from state emissions inspections. Finally, some states and localities employ public vehicle purchase directives to procure electric vehicles for their own public fleets, ranging from light vehicles to transit and school buses. Utility policies affecting EVs are discussed later in this report in Section I.B.

[20] Manufacturers and Models for New Qualified Clean Vehicles Purchased in 2022 and Before. Internal Revenue Service website [online] https://www.irs.gov/credits-deductions/manufacturers-and-models-for-new-qualified-clean-vehicles-purchased-in-2022-and-before#. Accessed June 17, 2023.

[21] Taxpayers may qualify for the new Clean Vehicle Tax Credit. [Online]: https://www.irs.gov/newsroom/taxpayers-may-qualify-for-the-new-clean-vehicle-tax-credit. Accessed June 20, 2023.

[22] A notice of proposed rulemaking was issued in 2023 to update the PEF values. Document ID: EERE-2021-VT-0033-0012 [online]: Regulations.gov. Accessed June 15, 2023.

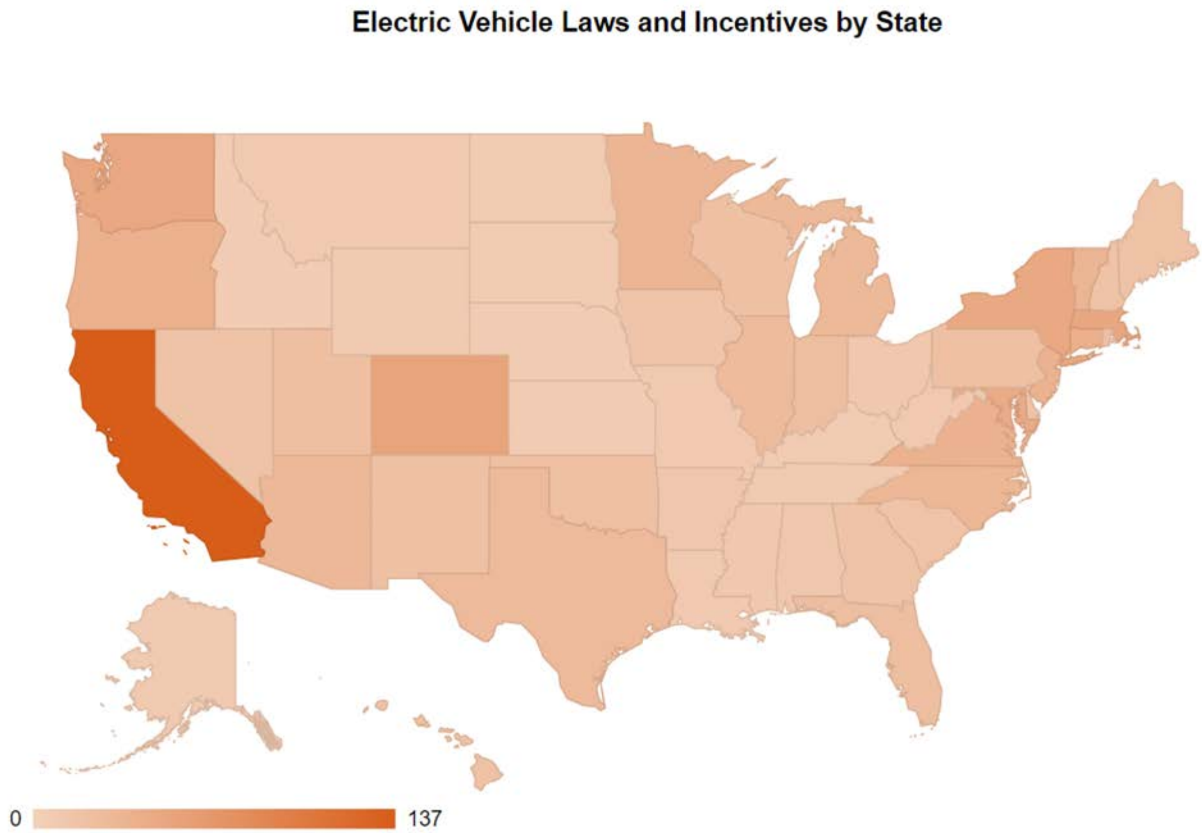


Figure I.7. Count of EV laws and incentives by state. The number of laws and incentives in place for most U.S. states ranges from 1 to 37, as indicated by intensity of shading, with California's 137 laws and incentives shown in orange. Data from the Alternative Fuels Data Center as of November, 2023[23].

Of special note is California's Zero-Emission Vehicle (ZEV) mandate, which has also been adopted by many other states. The ZEV mandate requires auto manufacturers to produce a number of ZEVs (either battery-electric or hydrogen fuel cell electric vehicles) and plug-in hybrid electric vehicles each year, based on the total number of vehicles sold in California by the manufacturer, to meet an annual ZEV credit requirement; more credits are awarded to a manufacturer per vehicle sold for ZEVs with longer electric-driving ranges. Credits are bankable for future use and tradeable/sellable among manufacturers. The seventeen "Section 177" states choosing to adopt California's low-emission vehicle regulations under Section 177 of the Clean Air Act and first applicable model year are presented in Table I.1. along with each state's light-duty ZEV market share for years 2019-2022.

[23] Alternative Fuels Data Center (AFDC). AFDC Laws and Incentives Data https://afdc.energy.gov/data/10373. Accessed Nov. 30, 2023.

Table I.1.States that have Adopted California's Vehicle Standards

under Section 177 of the Federal Clean Air Act[24] .

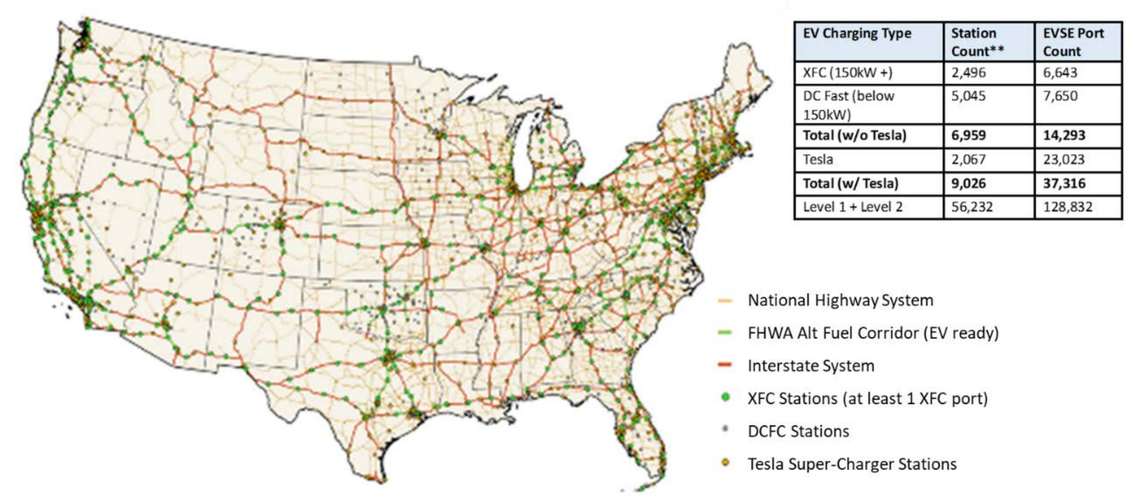
State[25]	First Applicable Model Year			Light-Duty ZEV Market Share 2019-2022[26]
	LEV Regulations		ZEV Program	
	Criteria Pollutant Regulation	GHG Regulation		
California	1992	2009	1990	12.26%
Colorado	2022	2022	2023	5.79%
Connecticut	2008	2009	2008	4.25%
Delaware	2014	2014	2027	3.32%
Maine	2001	2009	2001	3.07%
Maryland	2011	2011	2011	4.64%
Massachusetts	1995	2009	1995	4.70%
Minnesota	2025	2025	2025	2.68%
Nevada	2025	2025	2025	5.38%
New Jersey	2009	2009	2009	4.49%
New Mexico	2026	2026	2026	2.14%
New York	1993	2009	1993	3.22%
Oregon	2009	2009	2009	7.53%
Pennsylvania	2001	2009		2.32%
Rhode Island	2008	2009	2008	2.99%
Vermont	2000	2009	2000	4.58%
Virginia	2025	2025	2025	3.91%
Washington	2009	2009	2025	7.72%

[24] Source: California Air Resources Board,https://ww2.arb.ca.gov/sites/default/files/202205/%C2%A7177_states_05132022_NADA_sales_r2_ac.pdf May 13, 2022. Accessed November 15, 2023.

[25] https://ww2.arb.ca.gov/our-work/programs/advanced-clean-cars-program/states-have-adopted-californias-vehicle-regulations

[26]Alliance for Automotive Innovation Advanced Technology Sales Dashboard https://www.autosinnovate.org/EVDashboard

EV Charging Infrastructure



EV Charging Type	Station Count**	EVSE Port Count
XFC (150kW +)	2,496	6,643
DC Fast (below 150kW)	5,045	7,650
Total (w/o Tesla)	**6,959**	**14,293**
Tesla	2,067	23,023
Total (w/ Tesla)	**9,026**	**37,316**
Level 1 + Level 2	56,232	128,832

Figure I.8. Public fast-charging station locations in the continental U.S. as of November 2023 depicted along with major existing road networks and FHWA-designated EV-Ready alternative-fuel corridors. A combination of 5,045 direct-current fast chargers (DCFC), 2,496 extreme fast chargers (XFC), and 2,067 proprietary Tesla chargers account for 9,026 total public charging stations which together offer 37,316 charging outlets. These figures do not include Level 1 and Level 2 charging, which together comprise some additional 56,232 public stations, which total 128,832 charging outlets[27].

While most EV owners are expected to recharge primarily at home, public charging infrastructure provides EV users with locations for recharging while on the go—including on less frequent, longer-distance trips and other travel away from home—as well as affording critical recharging opportunities for EV owners without off-street parking, in apartment buildings or other multifamily housing, or otherwise without a home charger. As of December, 2023, nearly 60,000 public charging stations offering over 150,000 charging outlets had been installed in the United States. This infrastructure includes a combination of Level 1 charging (a standard 120VAC outlet powering roughly 4-to-5 miles of range per hour of charging), Level 2 charging (240VAC specialized equipment powering up to 25 miles of range per hour), DC Fast Charging (“DCFC”, 50 kW equipment powering up to 100 miles of range per hour of charging), and Extreme Fast Charging (“XFC”, 150 – 400 kW equipment powering 300 miles or more of range per hour). Figure II.6 depicts the locations of DCFC and XFC chargers in the continental United States as of December 2023. Charging station deployments have likely improved since the December 2023 study.

EV Market Future Possibilities

While U.S. EV market adoption forecasts included in this report vary widely, the consensus conclusion reached by the assessment study team is that EVs are likely to compose a significant

[27] U.S. DOE. (2023). Alternative Fuels Data Center. https://afdc.energy.gov/. Accessed Dec. 4, 2023.
** The station counts sum of XFC stations and DCFC stations is greater than the total (excluding Tesla) station count because equipment ID designations in the database may reflect multiple ports with different various maximum output power per port.

portion of LDV, MDV, and HDV markets by 2035. This conclusion was drawn from comparison of actual EV adoption trends with adoption forecasts and EV portfolio announcements by vehicle manufacturers. Figure I.7 summarizes U.S. EV light vehicle market projections through 2050 from 15 recent studies published between 2015 and 2020 by U.S. government agencies, national laboratories, energy companies, consultants, non-profit organizations, and international agencies. The estimates range from near-zero to 60% EVs in 2030 and 10 to 100% EVs in 2050. A series of major announcements since 2021 from light vehicle manufacturers and medium-/heavy-duty vehicle fleet owners may be drivers toward the higher ends of these projections[28].

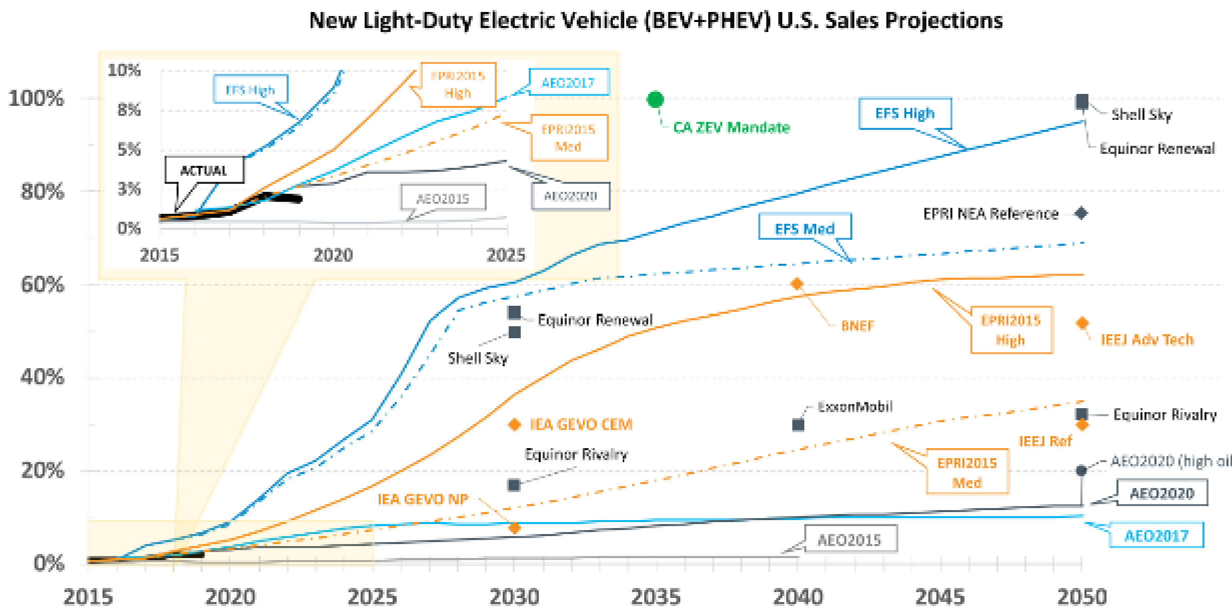


Figure I.9. Projections for electric vehicle share of new vehicle sales in 21 scenarios from 15 recent studies published by 12 unique sources. Future estimates range from a few percent to over 100% in 2035 and from 10% to 100% in 2050.[29]

For the purposes of this report, and based on previous Electric Power Research Institute (EPRI) analysis and vetting of experts from U.S. DOE's U.S. DRIVE government-industry partnership[30], three illustrative scenarios are proposed for future potential low, medium, and high EV light-duty vehicle market penetrations, as depicted in Figure I.8. By 2050, estimated annual EV sales range from 500,000 to 12 million (5% to 60% of all light vehicle sales) with between 10 and 170 million total EVs (2% to over 50% of all U.S. light vehicles) on U.S. roads. Since the EV market is still nascent for medium- and heavy-duty vehicles, fewer market projection studies have been published. This report considers an illustrative scenario based on a 2020 Bloomberg New Energy Finance analysis[31], as Figure I.9 depicts. By 2040, estimated annual medium- and heavy-

[28] Bomey, N. (2021). Honda to phase out gas cars, aiming for 100% electric vehicles in North America by 2040. *USA Today.* https://www.usatoday.com/story/money/cars/2021/04/23/honda-electric-vehicles-gas-cars/7348607002/
[29] Muratori et al. (2021). The rise of electric vehicles—2020 status and future expectations. Prog. Energy (3) 022002.
[30] U.S. DRIVE. (2019). Summary Report on EVs at Scale and the U.S. Electric Power System. https://www.energy.gov/eere/vehicles/downloads/summary-report-evs-scale-and-us-electric-power-system-2019
[31] BloombergNEF. (2020). Commercial vehicle sales forecast by class in the U.S., China, Europe, India, Japan and Korea. *Long-Term Electric Vehicle Outlook 2020.* https://bnef.turtl.co/story/evo-2020/

duty EV sales are 160,000 (nearly 30% of all medium- and heavy-duty vehicle sales) with 1.3 million total medium- and heavy-duty EVs (nearly 20% of all U.S. medium- and heavy-duty vehicles) on U.S. roads. While the scenarios shown in Figure I.8 and Figure I.9 are meant to be instructive contexts for discussion in this report, caution should be taken to avoid extrapolating these scenarios and in recognizing these projections as illustrative estimates, as the future of the EV market is still uncertain (as Figure I.7 illustrates)[32].

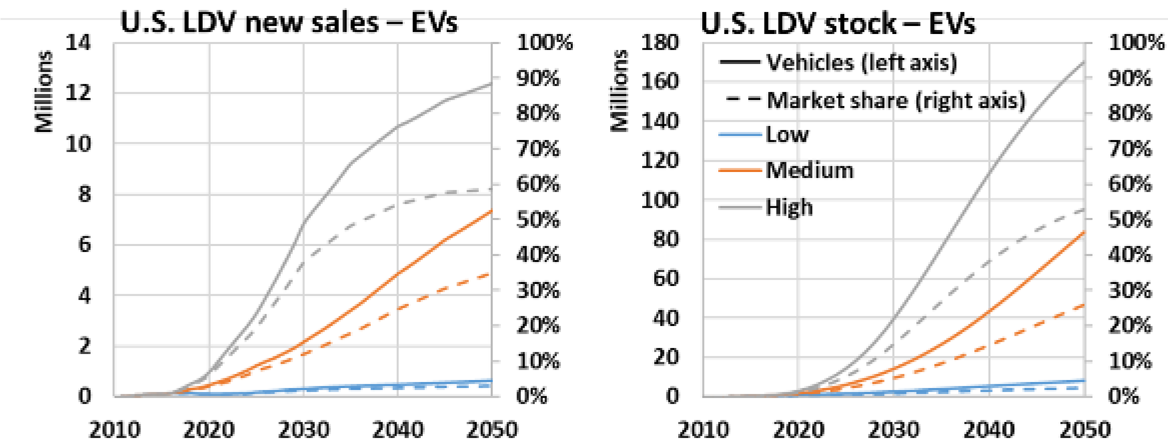


Figure I.10. Illustrative scenarios used in this report, based on previous EPRI analysis and vetting of experts from U.S. DOE's U.S. DRIVE government-industry partnership[30], for low, medium, and high EV light-duty vehicle market projections, shown both as annual sales (at left) and total U.S. vehicle fleet size (i.e., cumulative vehicles in service, at right). Solid lines correspond to number of vehicles (left axes) and dotted lines correspond to sales shares (right axes).

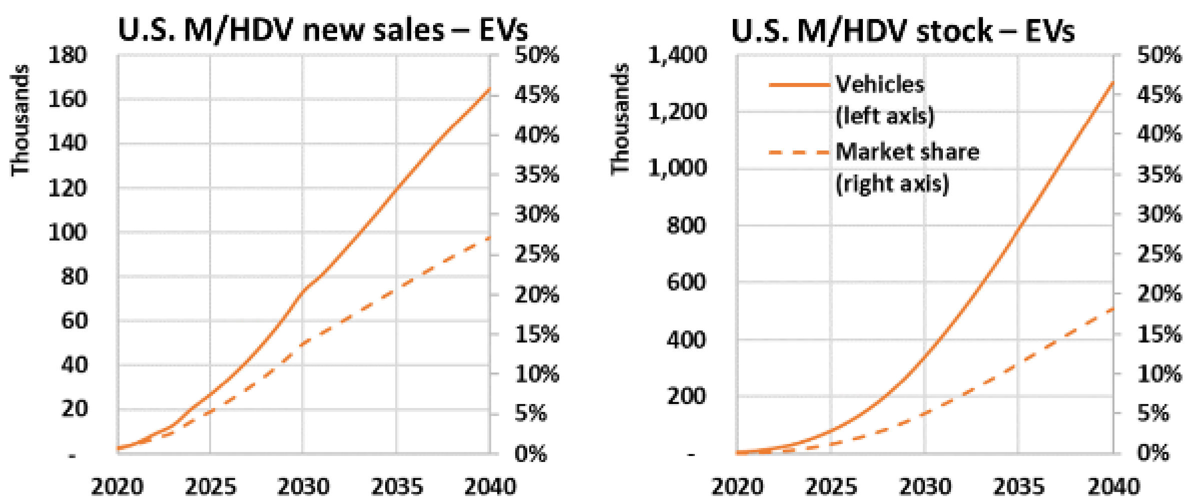


Figure I.11. Illustrative market projection scenario used in this report, based on previous Bloomberg New Energy Finance analysis[31], for medium- and heavy-duty vehicles, shown both as annual sales (at left) and total U.S. vehicle fleet size (i.e., cumulative vehicles in service, at right). Solid lines correspond to number of vehicles (left axes) and dotted lines correspond to sales shares (right axes).

[32] A 2022 NREL projection study of ZEV vehicles predicts higher estimates for M/HDV-EVs stock by the year 2030 than those provided in Figure II.9. See Ledna et al (2022): https://www.nrel.gov/docs/fy22osti/82081.pdf

B. U.S. Electrical Grid: The Foundation for Electrified Transportation

The U.S. power system encompasses more than 7,000 power plants[33] feeding a distribution system with 6,000,000 miles of wire serving 150,000,000 customers[34]. This immense system, integrated into every aspect of modern life, has provided inexpensive, reliable power for decades. It is also in the midst of a dramatic transformation that changes everything from how energy is produced[35] to how it is consumed[36]. Distributed energy resources (DERs) like rooftop solar generation and energy storage, the decarbonization goals for the electricity sector, and an increasingly engaged consumer base are changing how the power system is operated and maintained. The electrification of transportation, especially all aspects of the light-, medium-, and heavy-duty vehicle classes, is an additional element of this paradigm shift that needs to be considered to ensure affordable, reliable electricity service continues[37] [38].

Electric Utility System Basics

The electrical grid is the tightly coupled system that manages and delivers power from where and how it is generated to where — and how — it is consumed. Because electricity is not usually stored, most power is delivered for use at the time it is generated. The supply, transmission, distribution, and consumption of electricity in the system are therefore closely coupled and must be actively coordinated[39]. Significant changes in the consumption, such as large-scale electrification of transportation, can impact this coordination and require new infrastructure or operating methods. Elements associated with this coordination, such as the communications infrastructure and cyber secure operation of the electric grid components, also become significant drivers. Even under these shifting conditions, the electric grid is divided into three main domains: generation, transmission, distribution, per Figure I.10.

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[33] US DOE (United States Department of Energy). 2015. *United States Electricity Industry Primer*. DOE/OE-0017. Washington, DC.

[34] Warwick, Hardy, Hoffman, and Homer. 2016. *Electricity Distribution System Baseline Report*. PNNL-25178. Richland, WA.

[35] "In the year 2000, the United States produced more than 200 times as much electricity from oil than from solar energy. Over the next 15 years solar power generation grew by almost 30% annually, while oil-based generation fell by nearly 9% per year; by 2015 the amount of electricity generated from both resources were similar. In the years since, solar generation grew at nearly 40% per year while oil generation continued to decline, so that in 2018 nearly 3 kWh of solar power were generated for each kWh of oil-fueled electricity."
US DOE (United States Department of Energy). 2019. *Energy Information Administration: Monthly Energy Review April 2019*. DOE/EIA-0035(2019/4). Washington, DC. April 25, 2019.

[36] US DOE (United States Department of Energy). 2017. *Quadrennial Energy Review: Transforming the Nation's Electricity System: The Second Installment of the QER*. DOE/EPSA-0008. Washington, DC.

[37] Phadke, Amol, Aditya Khandekar, Nikit Abhyankar, David Wooly, and Deepak Rajagopal. 2021. *Why Regional Long-Haul Trucks are Primed for Electricity Now*. Berkeley, CA.

[38] NIST (National Institute of Standards and Technology). 2021. *NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 4.0*. NIST.SP.1108r4.

[39] Gopstein, AM. (2012). Energy Storage & the Grid – From Characteristics to Impact. *Proceedings of the IEEE* 100(2):311-316.

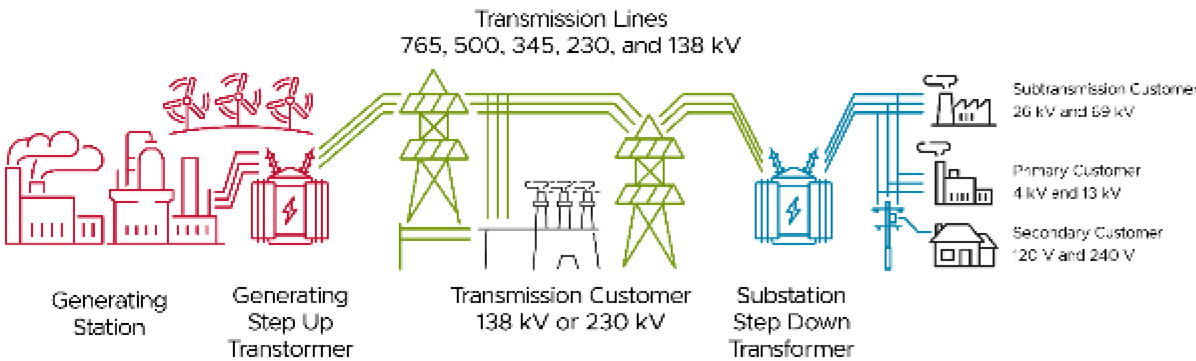

Figure I.12. Notional power system showing generation, transmission, and distribution elements.

Generation

Electricity generation is the process of creating electricity from other forms of energy and is the first process in delivering electricity to customers. This conversion may include a wide variety of primary energy resources and conversion technologies ranging from chemical combustion and nuclear fission, to flowing water, wind, solar radiation, and geothermal heat. As the primary electricity supply for the electrical grid, the Generation, including Distributed Energy Resources (DERs), is electrically connected to the Transmission or Distribution domains.

Historically provided by large generators that fed only the high-voltage transmission system, the scalability and modularity of modern generating technologies alters the physical relationship and points of coupling between generation assets and the grid, as well as the distribution of generation assets. Furthermore, many of these distributed generator assets are owned by the end customer, not the utility. Accordingly, this domain has been updated to reflect direct electrical interconnection with the distribution system that smaller scale and distributed generation assets may utilize. Desires to reduce GHG emissions are also changing the generation mix to include more solar and wind, often interfaced through power electronic inverters. This shift from traditional rotating machines is also influencing grid operations.

Transmission

Transmission is the bulk transfer of electrical power from generation sources to distribution through multiple substations. A transmission network is typically operated by a transmission-owning utility, Regional Transmission Organization or Independent System Operator (RTO, ISO respectively), whose primary responsibility is to maintain stability on the electric grid by balancing generation (supply) with load (demand) across the transmission network. RTO/ISOs set specific requirements and definitions to maintain this stability, while also operating a wholesale market for exchange of energy and ancillary services to meet these stability and operational constraints.

A transmission electrical substation uses transformers to step-up or step-down voltage across the electric supply chain. Substations also contain switching, protection, and control equipment. Substations may also connect two or more transmission lines.

Distribution

The Distribution system is the electrical interconnection between the Transmission system and end-use customers. It includes all points from substations that step-down voltage from the transmission system to the grid-edge and consumer. As with the Generation system, Distribution may contain DER, such as electrical storage, peaking generation units that supply electricity during times of high demand, and other assets such as community solar installations as well as EVs.

The electrical distribution system has a variety of design structures for supplying energy, including radial, looped, or meshed topologies. Radial topologies are the most prevalent, but many utilities are beginning to use looped and meshed topologies to provide multiple paths for electricity flow, or to help better isolate damaged sections of the electric grid. These deployments help increase the reliability and reduce the outage downtime.

The reliability of the distribution system varies depending on its structure, the types of configuration and control devices that are implemented, and the degree to which those devices communicate with each other and with entities in other domains. Historically, distribution systems have been radial configurations, with little telemetry[40] or actively participating elements. Grid modernization efforts are enabling customers to have more choice and control in their interactions with the power system. Due to this change from traditional power delivery, distribution systems often require more significant infrastructure upgrades and operational changes. Furthermore, operational considerations like cybersecurity are more relevant in the modern distribution system.

Distributed Energy Resources

Distributed Energy Resources (DERs) are smaller-scale generation sources or controllable loads that are distributed through the power system. As shown in Figure I.11, these are typically connected at the distribution level, with an increasing shift toward them being consumer-owned devices like rooftop solar and EVs, as well as traditional appliances or onsite battery energy storage. DERs have the capability to provide services to the electric grid via producing power for the grid or being able to reduce or shift load to help stabilize the power grid. As indicated above, DERs and an increasingly engaged electricity consumers are shifting how traditional power moves through the grid and are providing new venues to provide grid services to the power system. These services often require appropriate incentive structures to be put in place to help influence the customer device behavior to help maintain a stable grid. The deployment of DERs often increases measurement points and communications further into the distribution system, which enables better visibility into what is traditionally a “simple black box system” but also introduces considerations such as cybersecurity and information privacy.

[40] Telemetry is defined as measurement and status information that is communicated to an interested party (e.g., utility or load aggregator).

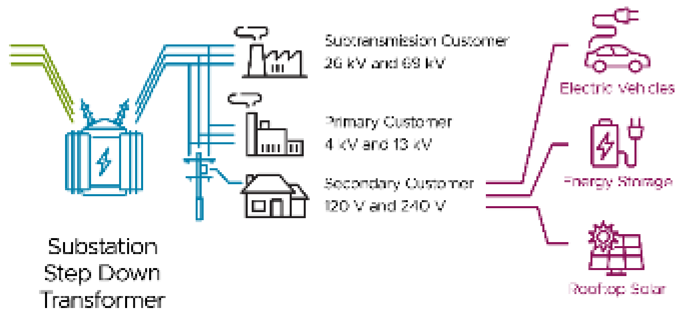

Figure I.13. Example Distributed Energy Resources (DERs).

Electric Utility Ownership/Operating Models

Electric utilities and their assets fall into two major categories of ownership: private (investor-owned) or public. Within these two categories, there are six broad classes of utilities:

- **Integrated** utilities are privately owned and vertically integrated, owning all the assets from generation to the customer meter.
- **Restructured** utilities are privately owned and operate where customers have a choice of retail electricity suppliers but may not own the generation assets.
- **Retail** utilities are privately owned and deliver commodity electricity supplies to customers using the distribution systems of restructured utilities to deliver the power.
- **Municipal** utilities are owned and managed by a local municipal government.
- **Cooperative** utilities are owned by the customers in a cooperative structure.
- **Other** utilities are owned and managed by public power districts or government entities, but don't directly fall into one of the prior categories.

The different categories of utilities share many common characteristics, especially in regard to delivering inexpensive and reliable power. Despite this similarity, different utility categories, especially along the private vs. public ownership models, can complicate integrating and deploying various technologies. Many of the structures and operating procedures within utilities have been built under traditional power systems concepts, with large generating assets providing the power that the transmission and distribution systems bring to a passive customer (they are just consumers, with no active role in the grid). Much of this operational paradigm was dictated by limitations in technology. However, changing technologies and more prevalent communication mechanisms are leading to a more empowered customer, with a much more active role in power system operations. Empowered by integration of new physical and informational capabilities, consumer devices can manage load, produce power, and otherwise support grid operations[41] in ways which defy the historical customer-utility relationship. As consumer and third-party assets gain capability to respond to economic opportunity beyond the traditional tariff structure, the relationships between asset owners and electric utilities will evolve.

[41] For example, by providing reactive power or voltage support along a distribution feeder.

The decision process and funding mechanisms available provide significant differences in how new technologies may be adopted, where they are adopted, and what capabilities may be supported. With the electrification of transportation, significant infrastructure investments may be needed, which may present challenges for smaller cooperative and municipal utilities. Additional mechanisms may be needed to ensure customers of the smaller entities can still access the benefits of transportation electrification.

Regardless of the ownership and operating model, electricity rates are the primary means for utilities to recover costs and generate income, as well as influence behavior. Through rates, utilities can incentivize consumers or businesses to reduce consumption during certain time frames. Due to the monopoly structure of utilities, rates are established through regulatory proceedings or governing boards. Special rates for consumers like large utility customers or EV charging also serve as a mechanism to try and influence customer behavior; special rates or incentive programs may be enacted to try and shift load or provide on-call resource availability to the utility. In some areas, utilities have begun to develop EV-specific rates to encourage certain charging behavior so that the increase in load does not necessarily require an associated need for additional generation assets. As larger numbers of EVs are connected to the grid – some with significant power requirements (e.g., large trucks or buses) – new, more complex approaches may be necessary and may provide opportunities for utilities and customers alike.

Electric Grid Operations - how the grid functions

Affordable, reliable power to U.S. customers and businesses requires the various generation, transmission, and distribution assets to be properly controlled and coordinated. To meet current and future demand, utilities must operate and control the flow of electricity in real-time for day-to-day operations but also plan for and anticipate future electricity demand incorporating changes. The changes can be in societal and customer preferences, as well as planning for investments that will provide grid capabilities to meet those preferences. While connecting EVs to the grid might appear simple on the surface – customers plug-in to charge and utilities meet that demand – it is much more complex and involved than it may appear to customers and policy makers. Beyond the connection point, utilities must continually balance the need for energy with the amount generated, maintain operational parameters (such as voltage, current, frequency) within tight operating margins, and monitor disturbances that could impact grid reliability and stability – considerations any significant change in load (such as EVs) can complicate. Investment decisions will need to be made today to meet tomorrow’s demand – not just accounting for increased demand. Those investment decisions will need to consider that in some instances, EVs will introduce new constraints or require new design considerations. Adapting the grid – which was designed for one-way power delivery – will require thoughtful consideration and planning as these new technologies are integrated into the nation’s legacy grid. Electric grid operations encompass many different time frames, including near-term characteristics all the way out to multi-year infrastructure investments. This section provides high level descriptions of the wide time horizon of grid operations, including both physical and economic aspects.

Basic Quantities/Operations

Near-term or "real-time" operations of the power system primarily focus on three aspects of the electric grid: maintaining frequency, maintaining voltage, and protecting the system and general public. Since electricity flows at nearly the speed of light, controlling the system requires immediate responses. If the frequency or voltage deviates too far from acceptable ranges, devices can start to malfunction or even be damaged.

Today most electricity is perishable, and the power grid must continually match the power produced with the power consumed. The frequency of the power system (60 Hz in North America) is a direct indicator of this power balance. If power generation and consumption are not balanced and the frequency deviates outside its acceptable operating band, protective devices will isolate power system equipment to mitigate serious and costly damage. If the power balance and frequency shift are too large, it can lead to subsequent outages. Such a scenario could result in a partial or full system blackout.

Another important operating constraint is maintaining voltage levels within specific limits to ensure proper flow of the electricity, as well as compatibility for the various customer loads. Much like the power balance and frequency conditions, adjustments must occur to maintain voltage within specified limits, before unfavorable conditions occur. If the voltage becomes too high or low, this can damage equipment. Even if within the specified limits, how quickly the voltage varies must be constrained, to help prevent equipment damage and abnormal behaviors, like lights flickering.

Safety of individuals and equipment are paramount for utility operations. At all levels of the power system, devices are deployed to protect the population and equipment from unexpected faults or contingencies. Circuit breakers, relays, and fuse devices are at all levels of the system (generation, transmission, and distribution) to separate or de-energize damaged portions of the power grid. This helps prevent members of the general public from being harmed by the high-voltage or high-current power, but also protects equipment from costly and longer duration outages. Some power system equipment (both the protective equipment and the device it is protecting), especially at the generation and transmission level, has lead times on the order of months to years. Preventing damage to those systems is necessary to support continued operations of the power grid.

All three aspects mentioned integrate into the overall operational quantity of "grid capacity". Grid capacity is the ability for the power system to provide electricity to a given location. Grid capacity values may change due to customer behavior changes, an equipment failure (such as a generator failing), or environmental effects like an extremely hot or cold day. The operational requirements for providing this electricity include maintaining the frequency, voltage, and overall protection capabilities of the electric grid. Depending on the limiting factor, this may require additional infrastructure like new generators or additional transmission or distribution lines, or an operational change in how existing and future assets are used (e.g., EVs).

Longer Term and Planning Operations

Beyond the near-term operations (typically 15 minutes or less), the intra-day operations are also important. In order to both maintain the reliability and affordability of the power, economic dispatch and stability studies are carried out. These often try to find the "best" combination of generation assets to meet the predicted demand on the system. The demand is predicted based on historical trends, as well as influences from the weather and any social influences (e.g., increased demand during the Thanksgiving holiday or half time during the Super Bowl).

Numerous factors influence the generation side of the equation, including fuel price and availability for generation. In general terms, fuel availability can also include the water head at a hydroelectric plant, or available generating capacity that may be influenced by environmental factors like minimum flow rates for seasonal fish migrations. The variability of renewable resources is also included in these calculations, often by requiring a source of standby generation if the wind or solar output drops. Many plants also do not start instantaneously, so a sufficient power margin and lead time must be factored in to bringing that asset to operational status.

While the economic and stability-based dispatch occur in concert with the "real-time" operations, all levels of the power system (generation, transmission, and distribution) often examine very specific scenarios, such as peak load or expected load growth. Traditional peak load studies often assume the hottest or coldest day of the year, traditionally when Heating, Ventilation, and Air Conditioning (HVAC) loads may be driving much of the power system demand. The deployment of significant DERs, like rooftop solar, is changing how system planners evaluate and assess anticipated generation needs. Now planners have to consider low load conditions and are performing studies to understand system implications during peak generation (i.e., low load conditions). Both peak load and peak generation/low load studies can also include scenarios where a power plant may be down for scheduled maintenance, or a known interferer will be present. Utilities will often need to bring additional assets online to cover these time periods, often at greater cost or greater environmental impact. In more drastic scenarios, the utilities may deploy approaches like load shedding or rolling blackouts to ensure overall system stability is maintained. Additional DER deployments and highly variable generation sources (e.g., wind and solar) further complicate these studies, requiring more detailed approaches and mitigation techniques.

Similar to peak condition and special scenario planning studies, utilities also examine load trends, trying to predict future changes that will impact load levels and load growth. These planning studies are required to help utilities evaluate anticipated trends and future scenarios on their system. Planning studies not only include future loads (such as EVs), but also the increasing energy output from DERs, or the potential services provided through VGI. The planning studies evaluate the overall grid capacity to meet anticipated customer loads and system behavior. Planning studies often examine infrastructure upgrades and significant capital projects, to help determine what solution may be best or how quickly it needs to be deployed; many capital and infrastructure projects require several years of lead time. Increasingly, utilities are exploring "non-wires" solutions like demand response or time-of-use rates to influence customer behavior and help defer infrastructure upgrades, or at least mitigate the long-term damage while upgrading their system. Capital infrastructure upgrades often require lengthy approval processes, from assessment of environmental impacts to determining rate adjustments to help finance the infrastructure upgrade.

The electrification of transportation, especially as more capable EVs become available, has the potential to impact all levels of operations. This includes not only the near-term operations by providing grid services through V2X or similar control mechanisms, but also in long term infrastructure upgrades to handle the increased load in unexpected locations. One example is fleet electrification where the utility has planned for "light" load conditions to accommodate lighting and HVAC loads. However, the location could need to serve significantly more load to "fuel" a fleet of electric trucks. Significant infrastructure upgrades could have lead times in years, which might be misaligned with industry needs.

Measuring/Assessing Reliability and Resilience

One of the primary missions of the U.S. electric power industry is to provide safe, reliable power to consumers and businesses. Reliability requirements are imposed at all levels of the power system, from generation all the way to the end customer. Reliability is quantified through standards-based metrics like IEEE 1366-2012 or NERC BAL, MOD, or SPC guidelines. Interconnection or utility-specific conditions may also apply, including any specific requirements from regulatory bodies like public utility commissions or the North American Electricity Reliability Corporation (NERC). Companies who fail to meet the reliability requirements are often assessed fines for non-compliance, and fines can be quite substantial.

While reliability is generally associated with providing the service within set operating bounds for credible contingencies (e.g., number of acceptable outages per year, acceptable duration of outages per year, required planning scenarios), resilience is often less well-defined. Resilience is often associated with the ability of the power system to handle unexpected or unknown events. Resilience may be associated with how quickly the system can recover after one of these events, or how the system robustly mitigates the impacts of these events before they cause significant damage. The DOE Grid Modernization program, along with other institutes like the National Academy of Engineers, has several efforts exploring how to quantify and evaluate resilience in the power system.

Both reliability and resilience evaluations are likely to need updates to their approaches and definitions with the increased electrification of transportation, along with DER integration in general. Many of the approaches are built around the traditional unidirectional power model (from large generation sources through transmission to the end-use load). Distributed generation and assets can provide power from the end-use loads, as well as enable concepts like intentional islanding and segmenting the power grid into smaller segments or microgrids. Properly quantifying and evaluating the impacts of these new operating paradigms, be the impacts beneficial or detrimental, will drive operating and planning decisions for the whole power system.

Grid Services

From balancing the variability of electricity supply and demand, to managing small, real-time changes in grid frequency and voltage, grid services encompass a wide range of actions that grid operators take on the distribution and transmission levels to maintain system stability, reliability, and economic efficiency. EVs, like many DERs, require grid services from the grid (primarily energy) and are equally capable of providing grid services to the grid. Many grid services can be provided by EVs simply by modifying how, when, and where they charge, and more extensive grid services are possible with bi-directional energy flow (V2G).

System operators procure grid services today for transmission level needs from a combination of utility-owned assets and through market mechanisms from qualified participants. For distribution level needs, grid services are primarily procured from the wholesale market, derived from utility-owned and operated assets, and to a lesser extent from end-use customers. Grid service needs and requirements are defined in part by reliability standards established by the NERC, by Regional Reliability Councils, or state-level regulatory bodies. Each region or market, then, has their own flavor of grid services, and the operational characteristics, definitions, and terms can vary widely. Additionally, transmission and distribution operators require different types of grid services and tend to describe these services in different ways.

Although there is a lack of widespread standardization in characterizing and classifying grid services, they are typically grouped by transmission or distribution level impacts and are described according to performance characteristics or operational objectives of the specific service. For example, some grid services can be characterized by performance characteristics such as: how much, how fast, and how long. These reflect the physical and temporal aspects of the service and resource providing it – how much the resource can increase or decrease output according to need, how fast the resource needs to respond to an event, and how long the resource must maintain the event. An example of a grid service operational objective could be “peak load management” or “frequency regulation.”

The following is a broad overview of common transmission and distribution grid services. While most of these grid services exist in today’s U.S. wholesale electricity markets, some are emerging grid service concepts.

Transmission Grid Services

Transmission grid services can broadly be grouped into two categories, energy and capacity services, and essential reliability services (ERS).

Energy and Capacity - Energy services are fundamental to balance supply and demand and grid operators in each ISO/RTO will utilize a day-ahead and real-time market to provide opportunities to purchase and dispatch electricity from generators or resources. This is done in a manner that aims to schedule least-cost energy delivery first, a term grid operators refer to as “economic dispatch.” Capacity services, on the other hand, ensure that there is adequate generation capacity from grid resources to meet expected electricity needs in the future. Four of the seven ISO/RTOs (ISO-NE, MISO, NYISO, and PJM) utilize capacity market auctions, where power plants or other resources make a "capacity commitment" in mega-watts (MW) to ensure the resource will be available to grid operators at some point in the future.

Essential Reliability Services - Most ERS can be classified as a variation of operating reserve services such as frequency response, regulating, contingency, and ramping reserves. While there are several variations of operating reserves, each capable of being provided by various resources, operating reserves broadly refer to the ability of a resource to increase output (provide "upward" reserves) or decrease output ("downward" reserves) based on energy system conditions and needs. Operating reserves are used for a variety of purposes, from responding to contingency events where system stability is jeopardized, to normal day-to-day operation, and are typically deployed in order of resource response speed (from very fast, to very slow).

Figure I.12 groups the various transmission grid services by category and displays the operational timeframe grid operators must procure or deploy the services.

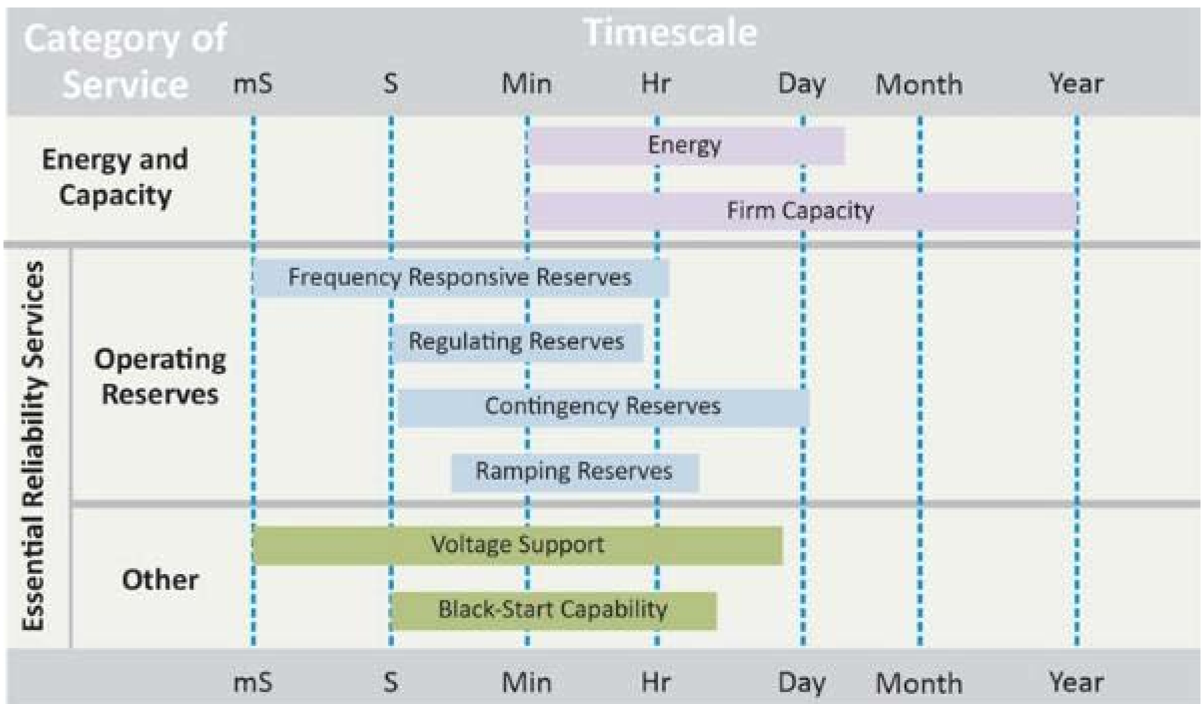

Figure I.14. Transmission Grid Services.

Distribution Grid Services

Grid services for energy (kWh) and capacity (kW) exist in the distribution system and are recognizable everywhere as "rates" – what you pay for electricity. Other grid services at the distribution level have traditionally been focused on maintaining power quality or ensuring the reliability of the distribution system. They are typically provided by distribution substations and pole and pad-mounted control assets, demand-side management programs, or managed through resource interconnection standards. In contrast to transmission grid services, markets for distribution reliability services are nascent.

The proliferation of customer sited DER is contributing to an increasingly difficult environment for distribution system operators (DSOs) to manage distribution capacity and power quality issues. However, the unique capabilities of DER and inverter-based resources – and EVs are prominent among them – can be leveraged for their ability to provide measurable grid services.

Some DSOs are exploring the capability of DERs to alleviate circuit capacity issues, or to facilitate emergency load transfers ("back-tie reliability services"). For these distribution grid services, at a certain volume they are equivalent to Non-Wires Alternatives (NWA) and can be considered within utility planning processes to offset or defer traditional infrastructure investments. Additionally, battery storage devices, or resources with smart inverter functionality such as EVs, have the potential to address multiple power quality issues on the distribution level, to include power smoothing, voltage management, and harmonic mitigation.

Figure I.13 provides a grouping of common distribution grid services by their operational objective and displays the timescale in which they need to be deployed to be effective.

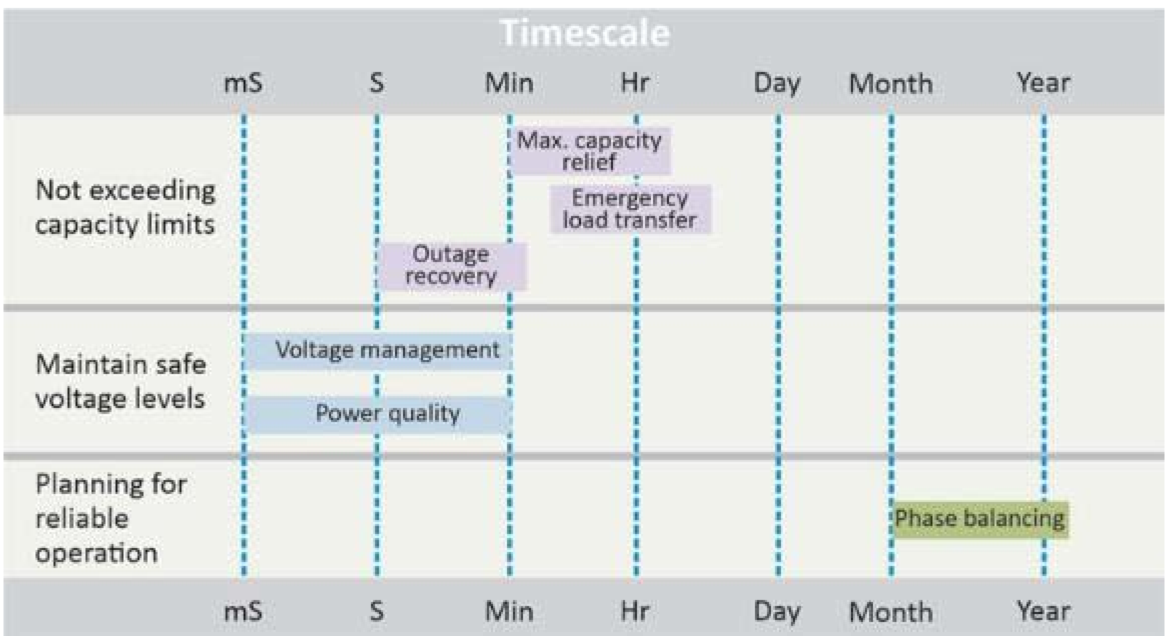

Figure I.15. Distribution Grid Services.

Grid-DER Services

Historically, grid services have been provided by large, synchronous generators. Today, technological and market innovations have enabled DER, including EVs, to provide broad benefits while maximizing the cost effectiveness of an energy system. DERs can be aggregated at the distribution level to a magnitude that they can potentially meet transmission-level grid needs. While the market for such DER aggregations is at present limited, FERC Order 2222 has required system operators to open wholesale markets for aggregations of DER to compete in providing grid services.

EVs, and DER more broadly, have the potential to become a competitive aggregated resource for grid services if it is compared in a technologically neutral manner to traditional, existing resources. However, as noted, there is widespread variation across the country, and even from transmission to distribution levels, around how grid services are defined, characterized, or classified. This confusion can present market access issues for DER when Order 2222 is implemented, highlighting an imperative to develop agreed upon grid service definitions.

Although this discussion has presented both transmission and distribution grid services separately, as viewed from an EV at the edge of the grid, the service is the same, and only the buyer of the service is different. From a grid edge perspective then, all transmission and distribution grid services can be collapsed into six groupings that DERs, and by association EVs, have the potential to address:

Energy Schedule Service: consume or produce a specified amount of energy over a scheduled period of operation;

Reserve Service: reserve some capability for increasing power generation or shedding load and act upon grid operator's signal within a short timeframe (e.g., 10-30 minutes) when dispatched in a contingency;

Regulation Service: increase or decrease real power generation or demand against a predefined kW base point following the grid operator's automatic signal every few seconds;

Black Start Service: start without an outside electrical supply and energize part of the electrical power system;

Voltage or Volt/Var Service: inject or absorb active or reactive power (or increase/decrease active/reactive loads) to correct excursions outside voltage limits; and

Frequency Response Service: detect frequency deviation and instantly inject (or absorb) active power to help arrest the frequency drop (or increase).

These broad categories encompass several similar or overlapping operational objectives and can simplify discussion around what specific capabilities EVs can provide. This grid services perspective, representing services both to and from the EV, can aid in understanding topics in the report as diverse as EV Time of Use rates, Smart Charge Management, and V2G, as well as emerging grid constraints and their potential mitigations. A final caveat for this discussion is that an EV's primary purpose is mobility, and its owner determines how its capabilities are employed. Grid services merely help define what is possible to provide, buy, or sell at the vehicle to grid boundary. Many of the subsections of Section II.C later in this report will explore portions of this in greater detail.

Regulatory Oversight

Many regulatory bodies exist to monitor various aspects of the power system. Some regulatory boards obviously focus on safe operations of the power system and will monitor standards and safety compliance. However, in the power systems context, regulatory oversight often refers to a body like a state public utility commission (PUC). These commissions are designed to provide pressures similar to a competitive market on utility monopolies. This is primarily to make sure the utility customer service needs are being met in a just and reasonable manner, often through examining aspects like utility investment applications. The utility commission helps ensure any investments or changes are well thought out and provide cost-effective value, while still supporting the customer requirements.

Regulatory oversight on the power system often has direct or indirect influences on the rate adjustments and making described earlier, the power industry's primary mechanism to manage costs, investments, and influence customer behavior. With the electrification of transportation, utilities, vehicle manufacturers, and charging service providers will be exploring different capabilities in the VGI space. Regulatory boards will be instrumental in evaluating if the investment and deployment of these new technologies is benefiting the customers and not degrading service performance.

It is important to note that privately owned utilities are primarily regulated by PUCs. Any changes that could affect the rate base must be approved by the PUC through a docket process, which can be lengthy and time consuming. Meanwhile, municipal, cooperative, and other publicly owned utilities under a certain size are not subject to PUC oversight because their inherent purpose is to provide power at the lowest cost while balancing other public or end customer priorities. The differentiation may provide more flexibility for these municipal, cooperative, and other publicly owned utilities to explore new business models and adopt new technologies earlier at the expense of profit maximization.

Regulatory boards are often involved in the approval of new infrastructure upgrades and capital investments. Traditionally, infrastructure upgrades have been justified by demonstrated load increases or changes to the system, often leveraging historical trends and information. These investments provided benefits that could be realized immediately. However, for disruptive technologies like EVs, this can require the regulatory board to approve upgrades in anticipation of load that may behave significantly different than other loads. The transportation aspect, including how customer behavior and usage will directly impact this, represent significant unknowns for the load planning purposes. These behaviors may not fit into traditional planning and regulatory constraints, further complicating upgrades and rate shifts to accommodate transportation electrification.

Grid Modernization – Adapting the grid to respond to customer and societal demands

As alluded to in the reliability and resilience discussion, aspects of the grid operation are changing, especially in response to customer and societal demands. Customers are wanting more control and choice over their energy, including the ability to produce their own energy with DERs. Grid modernization is moving to provide customers more information on how the electricity is being produced, or to select greener or more economic sources of energy when available. Many of these grid modernization technologies require additional investments from utilities and may be disruptive or contrary to traditional operating paradigms. To help alleviate some of the uncertainty, as well as explore further applications of technology being deployed, DOE has provided significant investments and guidance through its Grid Modernization Initiative and the Grid Modernization Laboratory Consortium[42] (GMLC). Throughout the utility deployments and DOE research, customers are still expecting affordable, reliable power which may require a utility to completely change their business model and strategies. This section highlights a few key elements of Grid Modernization efforts by DOE and utilities, with a particular focus on the electrification of transportation.

Need for increased observability into DER and grid-edge systems

Traditionally, power flowed from large generating plants down to the end customer and their load. Control was primarily on the generation and transmission side, with distribution being an uncontrollable or "dumb" characteristic of the system. With more distributed generation like rooftop PV, affordable energy storage, and the potential of EVs, this is no longer the case. Significant DER deployments (e.g., rooftop solar in Hawaii) have changed overall grid operations and can often have significant impacts on the power system stability. Therefore, it is now important to have increased visibility into the distribution system and its specific operating characteristics. This is needed to not only track and anticipate the behavior and influences of these devices, but also potentially provide control so they benefit the electric grid operations.

Most of the measurement devices and observability on the power system has been at the generation and transmission level. Devices like phasor measurement units, fault data recorders, and other high-rate telemetry have been adopted and deployed on the transmission system. However, the distribution system has not had the same influx of measurement devices and capabilities. Many utilities in the United States only have visibility at the substation level, providing little insight into how the distribution system may be behaving and impacting the transmission systems. The distribution grid is no longer a passive load and may be pushing significant amounts of power back into the transmission system, a condition not expected by many of today's planning approaches.

The ability to monitor, and ideally influence or control, the distributed and grid edge devices is instrumental in maintaining reliable, affordable power. With DERs (including EVs), customer end-use devices ("grid edge" devices) are gaining significant capabilities, especially when aggregated across a whole distribution feeder or system. Properly recognizing how these devices are behaving, as well as managing and leveraging their capabilities, can require additional measurement devices in the distribution system. While technologies like Advanced Metering Infrastructure (AMI) can provide some of this visibility (e.g., voltage and energy consumption at 5-minute or 15-minute intervals), managing how the data is used (both from a bandwidth and potential privacy perspective) will require great care, especially when customer-owned assets are being used. Many distribution utilities are beginning to deploy Advanced

[42] GMLC (Grid Modernization Laboratory Consortium). n. d. [online]: https://gmlc.doe.gov/ Accessed June 7, 2021..

Distribution Management Systems (ADMS) to help manage and control these increasingly connected resources. Many ADMS include a Distributed Energy Resource Management System (DERMS) component specifically to deal with elements like distributed generation, storage, and/or EVs.

Incorporating renewables/distributed energy resources/EVs

The visibility of grid-edge devices, like distributed generation and grid responsive charging mentioned in the previous subsection, covers one key aspect of their integration: observing how they are behaving to either help coordinate their operation or adjust other assets to account for their operation. However, the measurement and observability requirements are only a small portion of deploying DERs on the system. Grid infrastructure changes or updates associated with their deployment and regulatory concerns can also be significant portions of deployment and adoption.

As indicated in a couple of sections, the traditional power system operated under the assumption power flowed unidirectionally from large generation sources through the transmission system down to the distribution system customer loads. The infrastructure was built on this assumption. With increasing amounts of distributed generation, and the possibility for electrified transportation to provide services, this paradigm has changed. While the overall capacity of the power system to carry this reverse power may be a concern (e.g., if a community of rooftop solar is producing significantly more power than they consume), the change in the flow direction itself can cause significant changes in grid operations. This will typically be associated with improper assumptions by devices, such as that voltage on a distribution feeder drops as the distance from the substation increases – a topic that will be explored in the next paragraph.

Recall from an earlier subsection that the voltage on the system is one aspect that is controlled to remain between acceptable operating limits. In traditional systems, this voltage drops the further you get from the large-scale generation and must use corrective devices like tap-changing transformers or capacitive devices. The distribution system has such devices too, generally to adjust the voltage to make sure the furthest customer is still operating in the acceptable range. However, if significant DERs are deployed at the end of such a distribution system, the voltage can actually increase at the end of the feeder. If the distribution system has not been designed to accommodate or recognize this condition, it may result in the voltage regulation devices to work improperly (e.g., the “middle” of the feeder may be outside voltage limits due to the assumption the end of the system is the lowest voltage point).

Distributed energy resources, especially those that can produce power and push it back into the distribution system, also can cause problems with the protective devices on the system. Even in a simple protective device like a fuse, distributed generation downstream may prevent a faulted condition from creating enough current to break the fuse, leaving a damaged state on the system that is potentially dangerous. Scenarios are further complicated when the power direction can change many times during the day, such as with PV generation at night versus the day or when energy storage can discharge to provide services to the transmission grid.

Operating in these scenarios requires the protective device to recognize this condition and apply appropriate settings or controls.

Beyond the physical constraints, regulations associated with integrating DERs and the capabilities EVs may provide will require significant consideration. Operational regulations will need to provide guidance and limitations on what grid services and capabilities a device can provide, as well as operational aspects like who coordinates it and how is the service provided. While the distribution utility will have the immediate interest in how the DERs impact their system, other governance bodies may need to be involved. If the resource (or aggregation) is large enough, it may fall under transmission guidelines from FERC, NERC, or even the local transmission reliability coordinator. Decisions on whether or how to monetize the services to the end-use customer may involve the local utility commission or other regulating body. All of these regulatory aspects will have a direct influence on the overall operations and planning the electric grid utilities need to do to accommodate these resources.

The economics of DERs and grid-responsive charging of EVs will also be significant. Under traditional grid operations, distribution utilities bill customers for the amount of energy they consume. With more prevalent distributed generation, or the ability to use DERs and EVs to provide grid services, this model may need significant revisions. One major question is how utilities recoup costs for the infrastructure when a customer may self-provide outside of a few hours a day (or an emergency situation), so they require a functional and reliable power system connection, but only as a secondary source to their onsite assets (e.g., at night or on overly cloudy days). The utility billing and operating model needs to accommodate scenarios like this to ensure they can remain in operation and provide reliable power when needed.

Grid Capacity Considerations

Recall from earlier that grid capacity is the ability of the power system to provide electricity to a given location. Large-scale electrification of the transportation fleet, especially if medium- and heavy-duty vehicles are included, can significantly increase the amount of load on the power system. This increased load not only needs the appropriate power generated into the system, but also the appropriate infrastructure to deliver the electricity from the source to the vehicle. Other DERs, like rooftop solar generation, can help provide this need, but can also introduce additional operational constraints and capacity considerations. Local temporal capacity constraints may be ideal candidates for bi-directional capabilities (e.g., EVs, stationary storage).

Several studies have examined the large-scale capacity issues with the wide-scale electrification of transportation. Under prior EV adoption rates, many of these studies concluded the current generation fleet could provide the necessary power but may require shifting charging to lower demand periods (early morning) or utilizing market-based incentives to let the customer prioritize their energy needs. Some scenarios made use of transient stability models to support these conclusions, but these nearly all stop at the substation, neglecting any distribution-level equipment constraints.

Many of the grid capacity constraints associated with EVs are actually on the distribution network. In a macro-sense, the power generation and transmission systems can largely support the increased EV load, but individual distribution feeders may experience equipment overloads or operational issues. While many distribution systems have been upgraded to use higher voltages, there are still legacy feeders and systems operating at lower voltages. These systems are more likely to encounter overload and operational issues, especially if they exist in residential neighborhoods that have had negligible load changes over the years. These grid capacity issues need to be recognized to help determine additional infrastructure updates, or even how to properly use the EVs and other DERs. These issues will be highlighted further in Sections II.C.i and II.C.iv.

Many grid capacity analyses focus on a peak demand time or exercise the system during an otherwise heavily loaded time period. In normal grid operations, these are certainly conditions that may be stressing the system the most and influence the grid capacity to serve additional load. However, it is important to remember that these grid constrained conditions represent one particular scenario; grid capacity can also be constrained by other factors. Furthermore, many of these peak analysis approaches are not considering existing planned infrastructure upgrades, creating an inaccurate representation of the system.

While primarily a transmission system issue, the increased deployment of DERs has also made capacity associated with dynamic stability a potential issue. The operational controls of large generators and fleets of DERs can interact in unexpected ways, which can force the grid to operate at lower than “peak capacity” captured in the prior studies. Transmission operators will often derate a line to lower power values due to stability interactions. DERs are already known to cause similar behaviors in microgrids, alluding to the potential for these devices to impact the grid capacity of the larger system too.

Incentivizing and Influencing Customer Behavior

Regulatory and economic impacts to DERs and EVs have been discussed in a few sections. Under current operational methods, these are the two commonly used methods to influence customer behavior. Existing programs, like demand response or net energy metering, help incentivize the customer to adapt their behavior to either a “more friendly” grid impact, or a more predictable impact. Time-of-use prices or separate EV rates have been deployed to influence light duty charging and help mitigate impacts to the power system.

With the increase in DERs and the potential for large portions of an electrified transportation sector to provide grid services, incentivizing and influencing the customers will be just as important as the traditional generator and transmission operations. In aggregate, DERs can approach sizes of transmission or generator level devices, so their behavior will be just as important to grid operations. This is a continuation of the “smart grid” efforts DOE and the industry have been enabling over the last decade, with the load and end-use devices assuming an active role in power system operations, not just a “dumb device that can’t be changed”.

As with any operational control approach, customer behavior influences will need to be evaluated for any unexpected impacts or unintended consequences. With net metering and relatively small restrictions on the deployment of rooftop PV, many utilities are encountering issues with the "duck curve" phenomenon, where solar generation is readily available in the middle of the day (when load may be lower), but then not available in the evening peak. The significant increase in PV across a whole distribution feeder or region of the country can cause significant operational problems, especially managing the excess energy during the day and energy shortfall in the evening. The electrification of transportation has the potential to cause similar impacts. Customer behavior incentives and influences can both be a root cause and a potential solution to such unintended conditions.

C. Characteristics of EVs, Charging Environments, Charging Equipment, and VGI State of the Art

i. Electric Vehicles, Charging Equipment, and Charging Environments

This section provides a high-level background on electric vehicles, charging equipment, and associated charging environments. It includes a basic understanding of the technology and current performance capabilities, such as vehicular energy efficiency and range; and charging equipment types, power ratings, and charging environments for light-, medium-, and heavy-duty applications. Additionally, a discussion is provided on codes and standards and cybersecurity for the EV charging ecosystem.

Electric Vehicles

All-electric vehicles, which includes battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs), use electric motor(s), instead of the internal combustion engine of conventional vehicles, to propel the vehicle. BEVs run on electricity and must be plugged in to a wall outlet or charging equipment, known as electric vehicle supply equipment (EVSE), to replenish the battery when it is depleted. EVs – absent of combustion engines – don't emit harmful pollutants or greenhouse gases directly from the vehicle. Figure I.14 outlines key powertrain components that are common on BEVs today; component quantity and specifications will vary based on powertrain architecture as well as vehicle type, class, and application.

The onboard charger converts incoming AC (Alternating Current) electricity when charging at AC Level 1 or 2, supplied via the charge port, to DC (Direct Current) electricity to charge the traction battery. The vehicle's Battery Management System monitors battery status and communicates with the charging equipment; while the vehicle is being charged or driven, the Battery Management System monitors metrics such as voltage, current, temperature and calculates an estimated state of charge. The traction battery pack, commonly constructed of lithium-ion battery cells, stores electricity for use by the electric motor; via gearing, mechanical power is transferred from the electric motor to drive the wheels. The ("power electronics controller" shown in the figure manages the flow of electrical energy between the traction battery, power inverter, and electric motor – controlling the speed and torque of the electric traction motor as well as energy captured (via regenerative braking) by the electric motor for storage in the battery. Lastly, the DC-DC converter converts high-voltage DC power from the traction battery to the lower-voltage DC needed to run vehicle accessories and to recharge the auxiliary battery. The proper operating temperature range of these components – the traction battery, electric motor, power electronics (power inverter, DC-DC converter, and on-board charger), and other components – is maintained through a sophisticated thermal management system to prolong vehicle life and improve operating efficiencies.

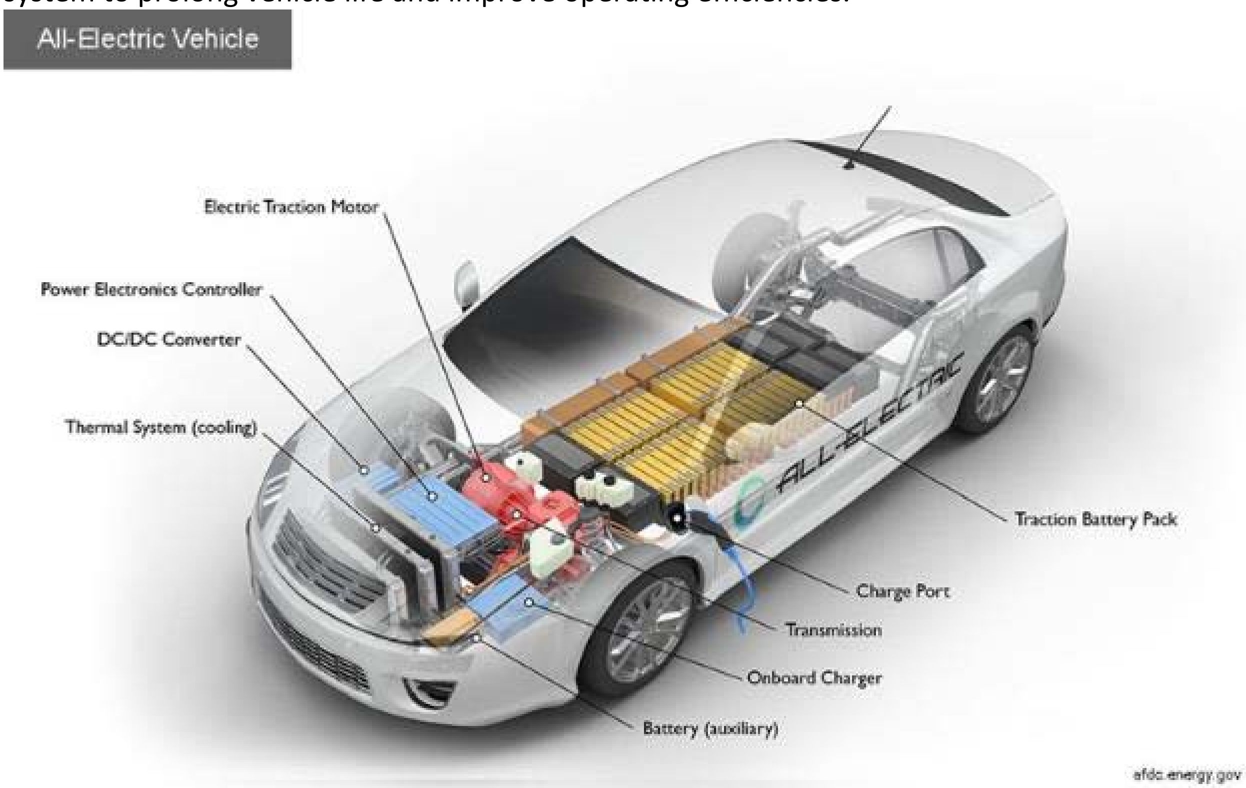

Figure I.16. Key components of an electric vehicle.

EV technological advancements have progressed dramatically in the last decade to the cusp of a major market expansion, riding a wave of significantly improved performance, driving range, lower costs, and widening model availability. Currently, the typical energy consumption of light-duty passenger car EVs on the road today is 0. 25-.40 kWh/mile [43]which, coupled with battery capacities ranging from 30 – 100 kWh, provides driving ranges of 100- 400miles [44],[45].. All light-duty EVs offered today can recharge using AC Level 2 and DCFC, with increasing numbers coming that are compatible with 300-400 kW DC charging. Medium- and heavy-duty EVs have also seen notable advances in recent years. Today, the typical energy consumption of medium-

[43] Alternative Fuels Data Center: Electric Vehicle Benefits and Considerations. U.S. Department of Energy [online]: energy.gov. Accessed June 13, 2023.

[44] All-Electric Vehicles [online]: https://www.fueleconomy.gov/feg/evtech.shtml. Accessed June 14, 2023.

[45] Power Search 2023-24 EVs. https://www.fueleconomy.gov/feg/powerSearch.jsp. Accessed June 20, 2023.

and heavy-duty EVs is 1.34 kWh/mile and 2.40 kWh/mile, respectively[46]. For current heavy-duty EVs (Class 7-8) with battery capacities of 500-760 kWh, this provides 200-300 miles of driving range. By the year 2050, medium- and heavy-duty vehicle energy consumption is expected to fall to 0.73 kWh/mile and 1.51 kWh/mile, respectively[46]. Most medium- and heavy-duty EVs will use DC charging exclusively, with potential heavy-duty Class 7-8 charging at 1+ MW.

Charging Equipment

EV charging can occur at a range of power levels with subsequent charging durations, which are based on both battery and onboard charger specifications that are necessary to meet the vehicle's class and application. Charging equipment for EVs is classified according to the power at which the batteries are recharged. Both AC Level 1 and AC Level 2 provide conductive Alternating Current (AC) to the EV, which the EV's onboard equipment converts AC to Direct Current (DC) needed to charge the batteries; AC charging connections can be found on both BEVs and PHEVs. DC fast charging delivers DC directly to the vehicle's traction battery. While many BEVs have this capability, this method is not typically available for PHEVs.

While most EV chargers today make a physical connection with the vehicle, in contrast, inductive (or wireless) charging equipment uses an electromagnetic field to transfer electricity to an EV without a cord or any physical connection. Charging times range from less than 20 minutes to 20 hours or more, based on the level of charging; the type of battery, its capacity, and state-of-charge; and the size of the vehicle's onboard charger.

The market for electric vehicle charging systems and the technologies themselves have evolved rapidly in recent years. Just 5 years ago, the majority of DCFC installed were 50kW EVSE, with L1 120 VAC (1.4 kW) and L2 240 VAC (3-19 kW) being predominant. By 2021, relatively significant numbers of 150 kW DC charging systems have become available for light and medium-duty vehicles with up to 350 kW at limited locations. For medium- and heavy-duty vehicles, manufacturers are working on the development of charging systems providing 1+ MW (and potentially up to 3.75 MW) of power. Megawatt-scale charging is key to enabling heavy-duty vehicle electrification although approximately 100 kW charging may be sufficient in applications with long dwell times (> 4 hours) and will be significantly more cost effective. Figure I.15 illustrates the currently available and expected (1+ MW) EV charging systems for vehicular applications, their relevant power ranges, and equivalence to the power demand of other common residential and commercial applications.

[46] Hunter, Chad, Michael Penev, Evan Reznicek, Jason Lustbader, Alicia Birky, and Chen Zhang. 2021. Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-71796. p.33 [online]: https://www.nrel.gov/docs/fy21osti/71796.pdf. Accessed June 13.2023.

Vehicle Class	Charging Type	Power Range	Illustration	Power Equivilance to Common Applications
Light duty	Level 1 120 VAC	1.4 kW		Hairdryer
Light duty	Level 2 240 VAC	3 – 19 kW		Dryer, Water heater
Light and medium duty	DCFC & XFC	50 - 400 kW		Small Office Bldg.
Heavy duty	High Power Charging	200kW – 3.75 MW	TBD	High Rise/ Retail mega-center

Figure I.17. EV Charging Systems and Ratings.

In addition, another form of conductive DC charging uses a pantograph – an apparatus mounted on the roof of an electric train, tram, electric bus, transit buses, or other heavy-duty vehicles – to collect high-power through contact with an overhead line. Charging connectors are a critical element of EV charging equipment and provide the link between the charging equipment and the EV. Figure I.16 presents the currently available and projected future charging connectors, associated standards, maximum power levels, and typical applications within North America.

Diagram	Main Standard/ System	Maximum Output Power, Volts, Amps	Standard Status as of August 2023	Application Notes
	SAE J1772 / AC Level 1, AC Level 2	19.2 kW AC, 208/240VAC., 80A	Released	Used for Level 1 and Level 2 in North America. Commonly found on home, workplace, and public chargers.
	SAE J1772+ IEC 61851 / CCS1	450 kW DC, 1000VDC, 500A	Updating	Used for DC fast charging most vehicles in North America. Generally installed at public chargers.
	IEC 61851 IEEE 2030.1/ CHAdeMO	400 kW DC, 1000VDC, 400A	Released	Used for DC fast charging select vehicles in North America. Generally installed at public chargers.
	SAE J3400 / NACS	250 kW DC, 410VDC, 610A	In-development	Used for both AC and DC fast charging. Standard is under development and is based on Tesla's design.
	SAE J3068	166 kW AC, 600VAC, 160A 450 kW DC, 1000VDC, 450A	Updating	Standard for both AC and DC charging using the IEC 61851 'type 2' connector for North America three-phase charging.
	SAE J2954	22 kW AC light duty, 480VAC, 30A 500 kW AC heavy duty, 480VAC, 670A	Released	Wireless power transfer standard for MD/HD vehicles is J2954/2. In U.S. the maximum power for light-duty is 11KW (WPT3).
	SAE J3105	1.2 MW DC, 1000VDC, 1200A	Released	Automated connection device to charge MD/HD vehicles. Variants include pantograph up or down and pin-and-socket.
	IEC 61851 IEEE 2030.1 / Chaoji	900 kW DC, 1500VDC, 600A	In-development	Sub-MW conductive charging for LD/MD/HD vehicles in Asia
	SAE J3271 IEC 63379 / MCS	3.75 MW DC, 1500VDC, 3000A	In-development	Conductive MW level charging for MD/HD vehicles.

Figure I.18. Electric Vehicle Charging Connectors[47].

In recent years, electric vehicle charging equipment is increasingly being deployed and the number of EVSE manufacturers and charge network operators has steadily grown. As of December 2023, the U.S. Department of Energy Alternative Fuels Data Center estimates there are approximately 64,000 public and private EV charging stations with more than 166,000 charging ports in the United States. This includes approximately 9,000 DC Fast stations with a total of 36,000 charging ports, 56,000 AC L2 stations with a total of 121,000 charging ports, and 228 AC L1 stations with a total of 800 charging ports. Presently, there are upwards of 20 manufacturers of EVSE with some of the larger manufacturers of AC L2, DCFC, and XFC being ABB, Siemens, ChargePoint, Bosch, Eaton Corporation, Tritium, Efacec, and Tesla. There are also a handful of manufacturers of wireless charging systems for electric vehicles including HEVO, WAVE, Witricity, and Momentum Dynamics. Major electric vehicle charge network operators

[47]. U.S. Department of Energy - Vehicle Technologies Office Electrification Program. *2022 Annual Progress Report*. Washington, DC: Vehicles Technologies Office, 2023. p.19, [Online]; [Vehicle Technologies Office Electrification 2022 Annual Progress Report (energy.gov)](). Accessed 28 Nov. 2023.

include, but are not limited to, ChargePoint, Electrify America, Tesla, EVgo, and Greenlots. In addition to the charger manufacturers above, there are also several manufacturers that make bi-directional DC EVSE, including Fermatta Energy, Kempower, Nuuve, Delta Electronics , Wallbox, and Ford Motor.

Codes and Standards: The successful implementation of large numbers of EVs requires simplified, streamlined interaction across the EV ecosystem including robust, comprehensive standards and protocols for EVs, charging systems, and interconnection with the grid. Standards are required to enable networked communications and energy management systems to interface with multiple devices and communications protocols and control strategies for charging equipment (individual or aggregated) to communicate with the grid. Harmonization of standards is critical for EV-Grid integration and interconnection, interoperability, and test procedures and are essential to further harmonize standards requirements across technology domains and to develop widely applicable interfaces. As shown in Figure I.17, grid responsive charging requires coordination and negotiation among many stakeholders, with each arrow representing an exchange of data needed to complete the charging transaction. Standardized communication protocols minimize barriers to this exchange of information and ensure that the process is maximally automated without requiring deep knowledge or involvement from the driver. Figure I.17 also provides an example of the standards that can apply within the EV charging ecosystem. With regards to standards, a particular challenge is that parts of the EV charging ecosystem fall under the jurisdiction of multiple standards development organizations (SDOs). While these SDOs have issued many standards that cover everything from the EV, EVSE, to grid interconnection, there has been limited coordination of standards between these SDOs to ensure harmonization.

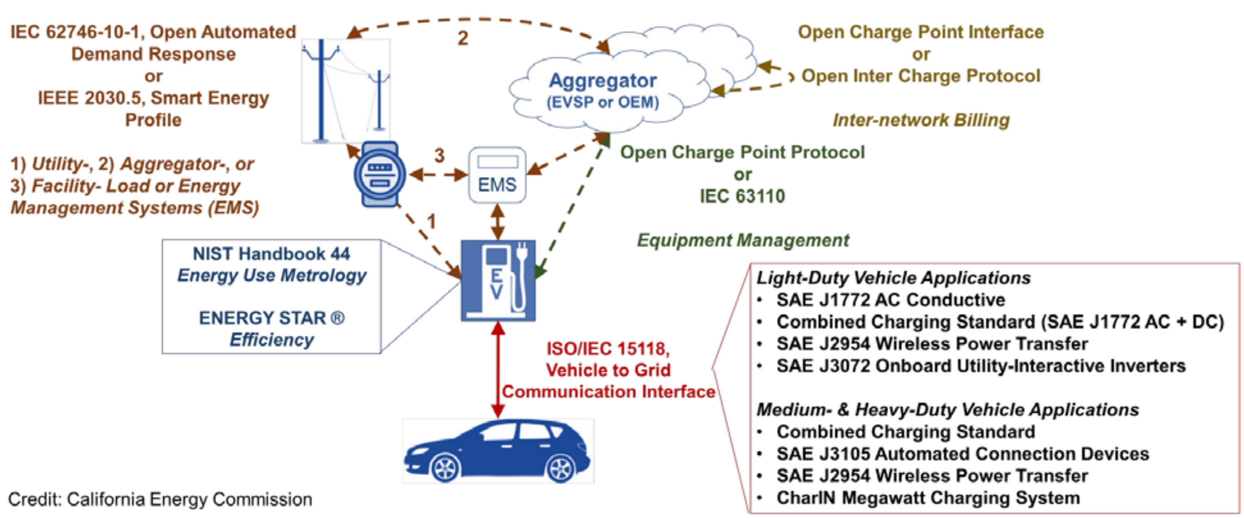

Figure I.19. Example of a Grid-Integrated Charging Equipment Design Archetype.[48]

[48] Crisostomo et al. (2021). Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment: Analyzing Charging Needs to Support Zero-Emission Vehicles in 2030. California Energy Commission.

Cybersecurity: Cybersecurity has become a major issue as EVs and their connectivity with external systems have become increasingly complex. Apart from AC Level 1 chargers, EVSE has evolved rapidly to be highly networked and maintain a wide variety of communication functions. As communication networks for EVs, EVSE, and external systems increase, attack vectors and cyber-physical risks also increase across the EV charging ecosystem. Since EVSE at workplaces and public charging facilities connect with many different EVs to provide charging services, assuring cyber-physical security is extremely difficult. As a result, compromised charging infrastructure poses a significant threat to electric vehicles and the electric grid. Presently, vehicle OEMs, utilities, and to a lesser extent EVSE manufacturers are addressing cybersecurity threats and vulnerabilities within their respective areas. But, to date, insufficient effort has been undertaken by industry to coordinate and address cybersecurity at the interfaces between these elements. Finally, from a cybersecurity perspective, it is important to emphasize that no EV ecosystem will ever be entirely secure and that threats will continually evolve.

Charging Environments

EV charging systems are installed in a variety of locations including residential, workplace, public, and commercial venues. Currently, most of the light-duty EV charging occurs at home (over 80%) dominated by single-family detached homes, 15% or so at the workplace, and the remainder at public venues (see Figure I.18). Typically, single-family homes utilize AC Level 1 or AC Level 2 charging. Notably difficult residential locations to site EV charging include multifamily housing due to complicated and often contradicting homeowner and renters' policies and business considerations for building owners. The increased adoption of EVs into the transportation sector is likely to result in more EV owners living in multifamily housing, which could increase demand for high-power charging in the public space and shift the composition of the existing charging pyramid. Workplace charging provides many positive attributes including EV consistency, long dwell times, and the ability for multiple EVs to share a single charger throughout the week, maximizing utilization and minimizing cost. Workplace charging also provides an opportunity to implement load management systems to maximize the use of a limited number of chargers.

Figure I.20. EV Charging Pyramid.

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https://www.energy.ca.gov/publications/2020/assembly-bill-2127-electric-vehicle-charging-infrastructure-assessment-analyzing

Light-duty EV charging at workplaces typically utilizes AC L2 charging, but occasionally may employ DC fast charging. With regards to light-duty EV charging at public venues, a variety of options exist including on the street, in parking lots and garages, at retail outlets, grocery stores, restaurants, recreational and entertainment centers, and at local and highway charging stations. The specific public venue will heavily influence the appropriate charging power level, be it AC L1, AC L2, DCFC, or XFC up to 400kW, or a combination thereof.

Presently, there are a limited number of medium- and heavy-duty EVs in small-scale demonstrations with charging established specifically for these EV demonstrations. However, the industry is preparing for wider-scale adoption of medium- and heavy-duty EVs and the charging requirements therein. For medium- and heavy-duty EVs, various depot and travel center charging scenarios are being considered. For depots, heavy-duty fleets fitting the short-haul trucking segment are targeted, which include return-to-home operations, limited daily vehicle miles traveled (VMT) (200-300 miles roundtrip), and long overnight dwell periods. Charging options of DCFC and XFC power levels are typically considered for depot applications, although AC L2 could work for Class 3-5 medium-duty local delivery vehicles. At travel centers for heavy-duty EVs, which exhibit short dwell times, megawatt level charging will be required. It is estimated that up to 3.5 MW charging will be required to achieve the targeted 80% state of charge (SOC) in 20 minutes of charging time for heavy-duty trucks. This could lead to total power requirements of 25-125 MW per site, which will pose substantial challenges with regards to connection with the grid. The addition of lower power DC charging (approximately 100 kW) at travel center locations for heavy-duty EVs with greater than 4-hour dwell times can shift the fraction of the total energy demand. However, minimum plug power requirements will depend heavily upon fleet operating profiles. In addition, while not as peaky as heavy-duty EVs using a set of 1+ MW EVSE at the site, slow charging for medium- and heavy-duty EVs at travel centers can aggregate and may create a relatively large overall demand. While greater vehicle battery capacities and ranges can shift requirements away from fast charging, even with long range vehicles, a robust fast charging network will be needed to enable heavy-duty vehicle electrification. For illustrative purposes, Figure I.19 presents a conceptional configuration of a high-power charging station for medium- and heavy-duty vehicles incorporating distributed energy resources.

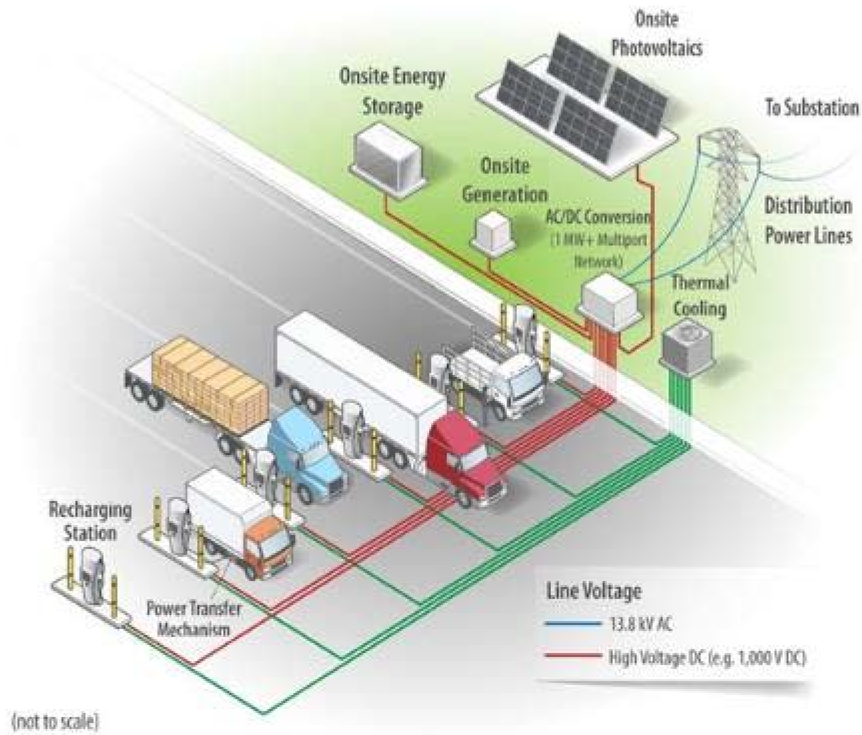


Figure I.21. Conceptual configuration of a High-Power Charging Station.

ii. Nature of EV Charging Demand on the Electric Grid

Charging of EVs can create varying and diverse levels of demands on the electric grid. The main factors contributing to varying demands include, but are not limited to, EV use patterns, charging infrastructure, dwell time, and EV battery capabilities. These demands can be characterized by charging power and energy requirements. For instance, the energy capacity of battery packs for a light-duty passenger car EV on the road today can range between 30 to 100 kWh and may be capable of accepting charging power up to 400 kW. The energy capacity of heavy-duty EV battery packs is between 500-760 kWh with potential charging power of up to 3.5 MW. Charging power varies based on several factors including EV capability, EVSE availability, charging use case, and available grid resources. All light-duty EVs are capable of charging at low power (AC Level 1 or Level 2) in a residential setting, but few can charge at XFC rates of 150-400 kW. It is expected though that the number of EVs with XFC capabilities will grow in the future. This implies that an EV could potentially slow charge (at low power) as well as fast charge (at high power) as the need and availability of resources dictates. This clearly shows the variation of demand that a single EV can project on the electric grid. Similar observations can be made for medium- and heavy-duty EVs; however, their charging power ranges vary greatly from light-duty EVs. Under these scenarios, if charging is unmanaged, increasing number of EVs connecting to the grid would create numerous challenges for utilities. This is particularly true at the distribution level, such as feeder voltage violations, system imbalances, flickers, equipment overloading, and large increases in daily peak loads.

For the purposes of the following discussion, a medium fleet market projection for the year 2030 is assumed for light-, medium-, and heavy-duty EVs totaling 14 million, 200 thousand, and 150 thousand, respectively. The projections are used regarding EV charging demand, although they have been made prior to several major state regulations and Federal initiatives were announced to encourage the adoption of EVs.

Energy Requirements: A series of straightforward assumptions and unit conversions allows us to place additional potential charging load from future EVs in the context of historical data. Assuming an average light-duty user travels 12,000 miles annually, consuming approximately 350 Wh/mi of AC energy, then each light-duty EV will require 4,200 kWh/year. This implies that for the year 2030 projection of 14 million light-duty EVs, the total energy requirement for all light-duty EVs will be 60 TWh/year. Similarly, for medium- and heavy-duty EVs the total energy requirement will be 15 and 25 TWh/year, respectively. As an aggregate, the electrification of the transportation sector based on these assumptions will require 100 TWh/year. In order to supply these charging loads reliably, the U.S. bulk electric grid will have to ensure sufficient generation and transmission resources.

For the year 2030 low, medium, and high EV sales scenarios, this translates into 1, 8, and 26 TWh of incremental energy generation including an additional 4.9%[49] of system losses. Detailed energy requirements in terms of energy generation needs for the projected light-duty EVs (under the low, medium, and high scenarios) are shown in Figure I.20. It is widely believed that the case of low EV market penetration and associated requirements for annual incremental energy generation is not realistic and is highly unlikely within the current market and policy environment. To provide a perspective of the energy requirements, the entire state of California consumed 260 TWh/year[50]. U.S. DRIVE, a public-private partnership focusing on light-duty vehicle innovation and efficiency enhancements, released a statement[51] on generation sufficiency stating it is sufficient to provide the growing energy needs of electrification. According to this statement, the energy requirements of the projections (performed prior to announcements of major state and Federal initiatives) can be met. Nonetheless, updated analyses should be performed considering potentially revised EV adoptions

[49] U.S. Energy Information Administration, "How much electricity is lost in electricity transmission and distribution in the United States?," 9 January 2019. [Online]. Available: https://www.eia.gov/tools/faqs/faq.php?id=105&t=3. [Accessed 21 August 2019].

[50] U.S. Department of Energy, Office of Electricity Delivery & Energy Reliability (OE) *State of California ENERGY SECTOR RISK PROFILE.*. [Online] p.1 . Accessed: 11/21/2021. https://www.energy.gov/sites/prod/files/2015/05/f22/CA-Energy%20Sector%20Risk%20Profile.pdf

[51] U.S. DRIVE. November 2019. Grid Integration Tech Team and Integrated Systems Analysis Tech Team Summary Report on EVs at Scale and the U.S. Electric Power System . [Online] p.V . https://www.energy.gov/eere/vehicles/downloads/summary-report-evs-scale-and-us-electric-power-system-2019.

including medium- and heavy-duty EV sales projections to fully understand future energy and generation requirements.

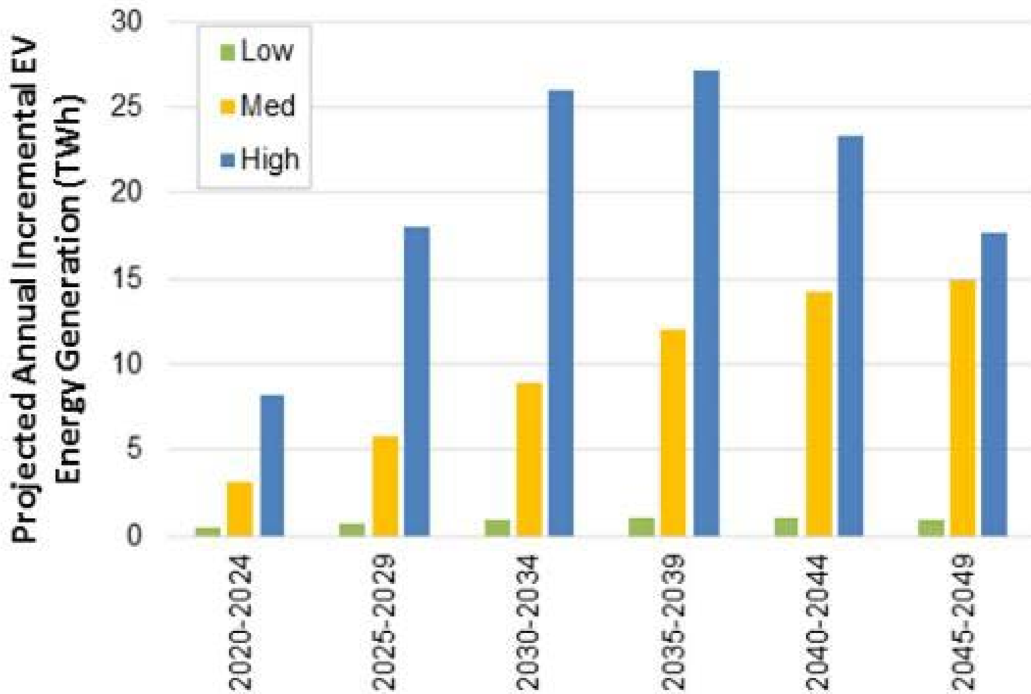


Figure I.22. Projected annual incremental energy generation to support EVs, averaged to five-year periods for the low, medium, and high market penetration scenarios.

Power Requirements: EVs are a unique load from the grid perspective as they are mobile, variable, and are expected to reach significant market volumes. This requires the charging network to be both available and reliable to enable mobility, as well as deployed in optimal locations. From the grid perspective, there are two main challenges – capacity planning and operations – for providing charging of EVs@Scale[52]. EV charging can imply the addition of a highly variable power demand. For instance, a typical light-duty EV connected to a DCFC has a charging profile that varies over time within the same charging session and may be partly "Constant Voltage (CV)" and partly "Constant Current (CC)". Figure I.21 shows the variation in charging power profiles of six EVs undergoing DC fast charging. The temperature of the battery pack may also play a significant role while fast charging an EV with the battery management system (BMS) altering charge rates correspondingly. The same light-duty EVs connected to low-power chargers (i.e., AC Level 1 and Level 2) will have significantly different charging profiles. This implies that the power demand

[52] "EVs@Scale" is defined as a future state of the U.S. Transportation Sector characterized by Electric Vehicles constituting a large portion of the entire on-road vehicle populations (e.g., > 25% market penetration).

from the same EV can vary significantly as it connects to chargers of different ratings.

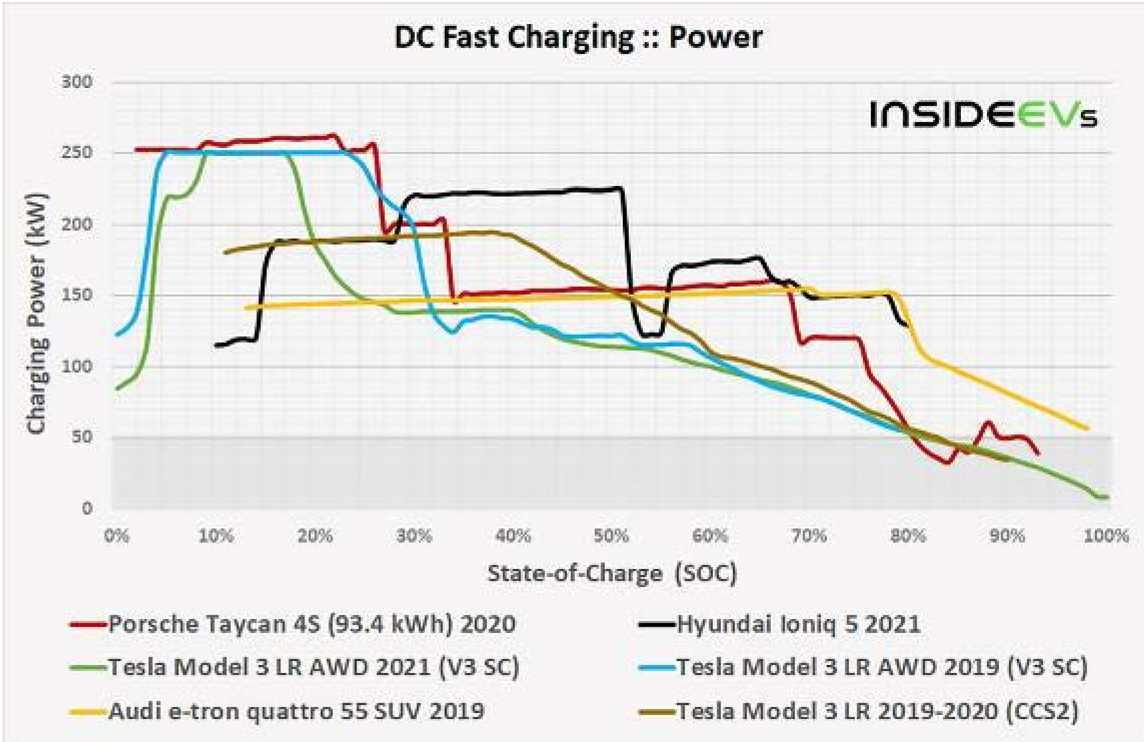


Figure I.23. Examples of Electric Vehicle DC Fast Charging Profiles[53].

One of the key goals introduced by the Biden Administration is the national deployment of 500,000 chargers[54], which can imply a variety of combinations of low- and high-power chargers. This deployment will be achieved through a combination of grant and incentive programs for states, local governments, and the private sector. Targets include apartment buildings, public parking, communities, and a robust fast charging system along U.S. roadways. The installed power rating of these 500,000 chargers can vary significantly and is dependent on their individual rating and purpose. In general, the cumulative power rating can vary between 10.9 GW for an "all low-power chargers" scenario to 214 GW for an "all high-power chargers" scenario. Beyond these 500,000 chargers, there is also charging infrastructure being deployed by and at charging service providers, local governments, multifamily housing, private residencies, and workplaces. In all likelihood, the installed charging load will be somewhere in between the two aforementioned limits. The power consumption for individual chargers and their aggregate will vary significantly and is dictated by the charging needs of the

[53] INSIDEEVs, Porsche Taycan (93 kWh Battery) Fast Charging Analysis: Very Good, Mark Kane, June 7, 2021.
[54] White House Fact Sheet [online]: https://www.whitehouse.gov/ostp/news-updates/2022/12/14/fact-sheet-new-innovation-agenda-will-electrify-homes-businesses-and-transportation-to-lower-energy-bills-and-achieve-climate-goals/. Accessed June 13, 2023.

connected EVs. The objective of the 500,000 chargers is to jumpstart the rollout of charging infrastructure that will eventually be needed to satisfy the charging requirements of a highly electrified transportation sector.

Dwell Times and Their Significance: Dwell time is identified as the idle/rest time between consecutive trips for a vehicle and hence can be utilized for “refueling” or “charging”. Factors that influence charging include EV usage, user convenience, EVSE availability, range requirements, time of day, and availability of power and energy. These are interrelated factors and will influence the planning of charging infrastructure, service agreements, energy management strategies, and any other behind-the-meter (BTM) assets. The importance and criticality of any of these factors tends to vary significantly for fleets and personally owned EV users based on their travel requirements.

Dwell times for EVs vary significantly and determine the charge rate and flexibility of charging profiles. For instance, a typical light-duty EV tends to have a dwell time of 8-10 hours while parked at residence every night; however, while traveling long distances, the same EV may stop for 20-30 minutes to charge, based on driver preferences. If the battery SOC for both cases is 20%, then dwell times will be quite varied. Based on these dwell times, the EV user can choose a low power (AC Level 1 or Level 2) for residential overnight charging but will need an XFC station to get a fast charge and continue their trip. In both these instances for the same EV, flexibility of charging power demand for the same light-duty EV are significantly different although the energy requirement is the same. The overnight residential charging allows a significantly large time window to control charging power and hence tremendous flexibility. On the other hand, the en route charging example does not have any flexibility and needs to charge the EV at the maximum rate as allowable by the EVSE, EV, and BMS. For low to no flexibility applications, charge control is not possible, and the power/energy demands may have to be met by a combination of the utility grid and Behind-the-Meter Storage (BTMS).

Charging EVs@Scale: The synthesis of charging requirements includes VMT, vehicle efficiency, infrastructure cost, utility service, etc. Accurate understanding of charging requirements for EVs can not only enable convenience for individuals, but also potentially revenue for fleets through provision of electricity from the vehicles back to the grid. It is anticipated that as the adoption of EVs and charging infrastructure deployment grows there will be impacts on the distribution grid. As a result, there is a significant emphasis on understanding charge management of EVs and distribution grid planning and operations.

For a local distribution network, the two key paradigms to consider are high volume of low-power charging and adoption of high-power charging at different venues. Charging power and energy requirements may overlap during stressful hours of the grid operations; for example, during early evening peaks due to charging of EVs at residences. In such cases, there are several challenges from an operational perspective including demand charges, voltage transients, and power quality disturbances. Past studies looked at planning-related challenges and issues such as line overloading, transformer overheating, and voltage sags for EV applications, but they did not consider EVs@Scale.

iii. Vehicle Grid Integration and State-of-the-Art

The primary goal of any EV is to provide transportation of goods and people. Charging must be achieved to obtain sufficient SOC prior to an EV commencing its next trip. However, there are times when charging may be constrained based on local facility or grid conditions such that sufficient charging may not be achieved. In general, there are two ways of addressing challenges of EVs@Scale charging – building out the electric grid to handle all conceivable charging requirements or adopting charge management techniques. The buildout of the electric grid to handle all conceivable charging scenarios at all potential locations is expensive, time-consuming, and not practical.

Adoption of charge management strategies coupled with the integration of DERs to balance the needs and requirements of EV charging can reduce the overall cost of charging and defer expensive electric grid upgrades. This approach can also enable EVs to provide grid services as an added value to the grid and a potential revenue stream for charging infrastructure owner/operators, as well as assist in grid integration. However, it is key to ensure that at the end of any charging session sufficient charge is imparted to EVs.

In highly constrained cases, reprioritization and reallocation of resources is required so that charging requirements are met within resource constraints. This requires foresighted and cohesive decision-making. The objective of VGI is the development of a practical framework that facilitates the charging of EVs at lowest possible cost, with high reliability and resilience, and minimal impacts to the electric grid. Furthermore, VGI can reduce ground level criteria pollutants and greenhouse gas emissions and mitigate the need for grid buildouts. VGI entails a tight coupling of charging infrastructure with the electric grid to enable a seamless and interoperable charging experience for all types and classes of EVs. VGI needs to facilitate the constantly varying charging needs of EV fleets with the needs of a highly complex and dynamic electric grid.

The VGI ecosystem is expected to have a flexible architecture with several entities performing specific roles as shown in Figure I.22. These entities (or actors) include EVs, EV owners, utilities, aggregators, EV service providers (EVSP) and others which are needed for enabling specific VGI objectives. The VGI framework should also be scalable, implying that it is extensible from a single EVSE to a large depot housing several tens or possibly hundreds of EVSE. Once the technical aspects of VGI are harmonized, adopted, and perhaps even standardized, a much smoother EVs@Scale transition is expected. The two main functionalities that enable VGI are V1G and V2X as described next.

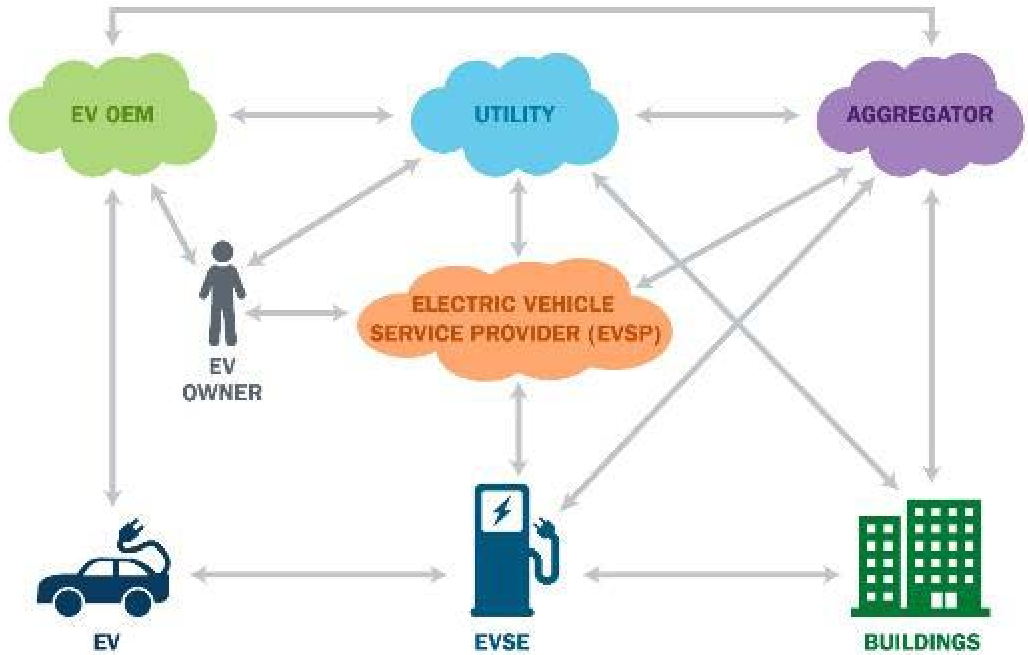


Figure I.24. VGI Ecosystem and Potential Actors.

V1G: V1G implies modulating unidirectional flow of power from the grid/facility to the EV that leads to controlled recharging of EV battery packs. This modulation of power flow can be either performed on AC or DC charging power and depends on the capabilities of the EVSE being used but may result in longer charging times. In general, a longer dwell time is needed for performing V1G and helping meet charge management objectives of the grid and EV users. V1G has the potential to provide several grid services which are essential to maintain reliable operations of the grid.

V2X: Vehicle-to-Everything (V2X) is transferring power from the EV back to the home, building, facility, and/or grid (i.e., V2H/V2B/V2F/V2G) by discharging of the battery pack. With an increasing complexity, this battery discharge can be fed to either a home, building, facility, or even the electric grid. A higher degree of control and coordination is required for feeding power to the grid as compared to feeding an islanded facility or home. V2X has the potential to provide several grid services as well which augment reliability and resilience of either local facilities or the grid.

EV Charge Management: A fundamental objective of any charge management scheme is to ensure that the EV charges to the requisite level by the time of departure. To bridge the needs of the EV users and the electric grid, charge management is required and can be performed by utilizing V1G or V2G. V1G has served as the primary mechanism facilitating charge management due to its relative ease of implementation and hardware requirements. Charge management of EVs is influenced by a number of external factors including the price of electricity, BTMS status, and local DER status. Charge management can vary in complexity from fairly simple price signaling to very complex smart charging strategies. The costs and benefits of charge management strategies are related to their complexity and rigor. EV charging strategies can be categorized as passive management, active management, or smart charge management.

Passive Charge Management is the control of EV charging that is primarily based on price values or consumption limits that may either be fixed or communicated as needed. The decision-making can occur at the EV, EVSE, or on a facility level based on the architecture. This is the easiest charge management that can be implemented in practice and has limited benefits in enabling VGI. Typical strategies include TOU or programmed response.

Active Charge Management is the management of how much charge power EVs are receiving and is typically performed by an external entity such as a facility management system, an aggregator, or charge network operator (CNO). Decision-making of charge allocation typically occurs at a higher level with regards to the EVSE/EV. Active charge management requires a greater level of rigor to implement including the implementation of standard communication protocols and infrastructure than passive charge management but yields greater benefits. Types of active charge management strategies include round robin charging, equal split of capacity, and automated demand response. Here, as information from individual vehicles is not considered in the charge management strategy, the vehicle may not receive a full charge by the time required by the owner.

Smart Charge Management (SCM) is the effective control and optimization of the charging ecosystem and is essential to EV-Grid integration. SCM emphasizes the identification of pathways to reduce the potential grid impacts of EVs@Scale, while providing enhanced value for EV/charging/grid systems including reduced costs and increased opportunities for grid services. SCM can also facilitate the provision of grid services from EV charging, including, but not limited to, peak load shaving, demand charge mitigation, voltage support, frequency regulation, and integration of renewable energy generation. SCM strategies are a means to tightly integrate EV charging loads with the grid. SCM is regarded as the most complex form of charge management as it utilizes advanced two-way communications and includes constraints, needs, and objectives of almost all management actors (grid operator, aggregator, CNO, and EV owner) in the EV charging ecosystem. SCM enables decisions for optimal charging without any negative impacts on the grid and is typically complex, rigorous, and expensive, but can enable most grid services and ensure reliable charging of EVs.

D. Sector Coupling

Energy is a foundational pillar of almost every aspect of society. The aggressive goals to decarbonize the nation's energy system, with goals of decarbonizing the U.S. electric grid by 2035 and the American economy by 2050, and an increasing focus on electrification – of transportation, of industry, and of commercial and residential needs – will increase the energy system's importance. A significant element of that new future includes the vision of an electrified transportation sector. Bringing the power and transportation sectors together will create greater interdependencies than currently exist, making it imperative that long term strategic issues are proactively evaluated and considered. The sectors will need to consciously plan and adapt – not only in isolation but in the context of each operating together – to maximize national and societal benefits and minimize the risks without compromising the primary mission of each sector. The coupling of these two sectors will require careful and disciplined consideration.

Sector Coupling, a term developed in European Union energy transition discussions, provides an analysis perspective that can reveal the best paths forward to achieve societal goals while anticipating the effects of interdependence on each sector. The ultimate goal is to make each sector stronger by their linkage – each more efficient, more capable, and more useful than they were before. Evaluating the transition to transportation electrification with Sector Coupling in mind can help to answer broader policy and implementation questions. One important question relates to the reliability of the electric grid. For example, if an essential service – the movement of goods, services, and people – comes to rely heavily on electricity, are present reliability and resilience numbers acceptable? Today, a power outage can have mild to severe consequences on citizens and businesses. If transportation is impaired at the same time, the acceptable levels of resilience and reliability may be higher than it is today. The answer however informs neither policy nor research until it can be quantified. Sector Coupling will require expertise from the transportation sector, developing a structural understanding of the transportation system, quantification of reliability and resilience, and other factors of present-day internal combustion engines and the infrastructure that sustains them. Similar expertise must be employed to frame the electric sector in similar terms, such that comparisons can be made, and then a future charted. Other sectors of society are already far more coupled with the electric sector and can provide some perspective on the matter.

By referring to Figure I.1, U.S. Energy Flows Diagram one can see that in 2020 the transportation sector was 90% dependent on petroleum, 5% on biomass, 4% on natural gas, and slightly under 1% on electricity. It could be said that the electric and transportation sectors are only *weakly coupled,* with few interdependencies. By comparison, the residential and commercial sectors were both approximately 50% dependent on electricity, and are therefore *strongly coupled*, with extensive interdependencies. Viewed from the opposite direction, as depicted in Figure I.23, approximately 96% of all electricity is consumed by the residential and commercial sectors. All three sectors have influenced each other's structures and performance characteristics extensively, literally from the foundations up.

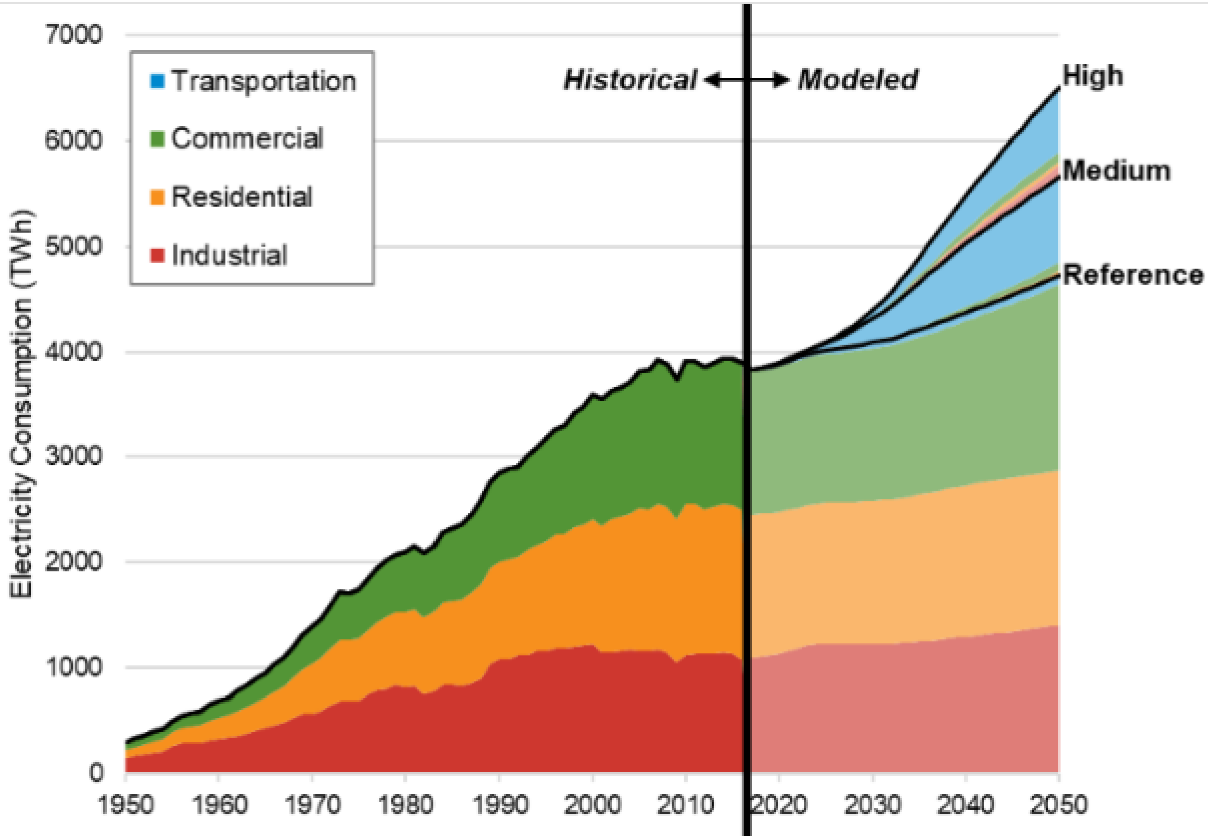


Figure I.25. U.S. Electricity Consumption by Sector.

For over 100 years, the residential and commercial sectors have influenced the design and operation of the electric sector, while the transportation sector has not. Transportation electrification will elevate the importance of transportation electricity use and may require a reassessment of how the grid is designed and operated. The chart above shows potential additional electricity use by the transportation sector, stressing the importance of assessing the implications now. Given this historical lens, electric utilities expect their most important users to remain perfectly immobile, which is a valuable characteristic when it comes to deploying and maintaining expensive physical infrastructure that lasts for decades. Additionally, a home or business uses electricity throughout the day with relatively predictable variation, but they do not require that the day's entire electric energy be delivered in one short block of time. Increasing electric demand from electric vehicles break both norms for electricity planning and operation and has been the subject of extensive DOE research. Strong Sector Coupling will require a different scale of analysis with emphasis on the big picture and the long term, both because of the extent of the interdependencies and the time needed to alter the structures of the electric grid.

Strongly coupled sectors have the capacity to enhance both benefits and risks, but a brief discussion of risk is illustrative. Risks can originate in one sector and propagate into the other, sometimes to amplified effect. Extreme weather or environmental events, such as wildfires, expose both sectors to the same risk simultaneously. Risks can transform as they cross sector boundaries. A cyberattack may affect electric vehicles, but the risk to the electric sector would create an energy instability risk – the same as if the roles were reversed. Evacuations due to extreme weather events or even temporary work stoppages at busy shipping ports may synchronize charging needs at local or regional levels, with risk for both electric and transportation infrastructure. Decarbonization and carbon pricing could have ramifications over long time horizons that may require economic risk analysis across sectors to assess risk.

One tool that will be employed in Sector Coupling analysis is Grid Architecture. Grid Architecture is a discipline with roots in system architecture, network theory, control engineering, and software architecture, all of which is applied to the electric power grid. An architectural description is a structural representation of a system that helps people think about the overall shape of the system, its attributes, and how the parts interact. It facilitates regulatory and policy dialogue and implementation, it helps identify structural barriers that define the limits of grid behavior, creates new structure to enable new capabilities or strengthen grid properties such as resilience, and identifies gaps in theory, technology, and organization. Most of all, Grid Architecture provides insight to stakeholders so they can make informed decisions about grid modernization. Combined with similar methodologies to frame the transportation sector, valuable insights can inform R&D and policy.

Sector Coupling can also be assessed through simulation and modeling. Electric vehicle RD&D has made extensive use of simulation and modeling for a wide variety of purposes, from the physics of components to behavioral models that predict travel patterns of populations of EV adopters. Electric grid RDD&D has done the same, but Sector Coupling analysis will require a new range of needs, both economic and engineering in nature. The North American Energy Resilience Model (NAERM), a large-scale simulation environment designed to assess interdependencies between electric, natural gas, and communications infrastructures nationwide, has begun the incorporation of some transportation aspects, but this and more varied efforts will be required over time. DOE has the foundational tools to identify electric vehicle travel and geospatial-resolved charging load to address sector coupling. These tools will be essential in establishing a coupled grid-transportation charging infrastructure that intelligently integrates EVs with the grid.

II. EV-Grid Integration Study Results

This section contains the results of a DOE study titled "Integrating EVs Onto the Electric Grid".

This section describes the problems and proposed capability solutions that are necessary for integrating EVs onto the electric grid. It also describes the challenges for achieving the proposed capability solutions and requirements for standards to enable those capabilities.

The study incorporates conclusions from multiple studies that have been performed by DOE, the national laboratories, and industry stakeholders. Each of the high-level study results provides references to the study details. The Department put out a Request for Information (RFI) to solicit stakeholder feedback on VGI and conducted other stakeholder activities. These are covered by Section IV.

The goal of integrating EVs onto the electric grid is to harmonize the EV transportation mission with the U.S. electric infrastructure mission, fulfilling societal and environmental goals. This EV-grid integration strategy is based on the following rationale:

- While fulfilling their primary mission of providing transportation, EVs provide significant petroleum and emissions reduction benefits. Integration of EVs with the grid offers further benefits and increased flexibility for vehicle owners and the grid.
- EVs can use electricity from a variety of sources, which has potential to minimize costs over the long run. Over time, utility companies can switch to the least expensive green and carbon neutral fuels for their generation plants/sources. This flexibility in generation source fuels is key to decarbonization of the U.S. transportation sector thus breaking the single fuel source dependency that petroleum-based fuels have held on U.S. roadway transportation for more than a century.
- It makes economic and environmental sense to displace petroleum usage with electricity usage because, compared to conventional vehicles, EVs have superior energy efficiency capabilities in terms of energy conversion and energy reclamation. Electric motors are much more efficient than internal combustion engines at converting energy to work that moves the vehicle down the road. EVs can also reclaim energy when coasting downhill or braking. These EV efficiency effects reduce the transportation sector's contributions to global warming that are attributable to waste and conversion energy. This allows EVs to be the least cost alternative of transportation fuel and least energy consuming mode of transportation over the long run.
- EVs' transportation mission can be harmonized with U.S. national climate change, sustainable energy, energy security, and pollution reduction goals. EVs can use energy supplied by renewable energy resources such as solar, wind, and hydropower. This reduces emissions attributable to the transportation sector and can increase the utilization and return on investment (ROI) of renewable energy resources. By displacing

petroleum fuel from foreign sources, EVs increase U.S. energy security by using a broad range of domestic sources of energy.

This report section presents results of a study that examines the research, development, and demonstration opportunities, challenges, and standards needed for integrating electric vehicles onto the electric grid. The technical study topics are in the document as follows:

An evaluation of the use of electric vehicles to maintain the reliability of the electric grid is presented in Section II.A. This is followed by an evaluation of the impact of grid integration on electric vehicles in Section II.B. The impacts to the electric grid of increased penetration of electric vehicles is discussed in Section II.C. Section II.D describes the research on the standards needed to integrate electric vehicles with the grid. The cybersecurity challenges and needs associated with electrifying the transportation sector is covered in Section II.E. An assessment of the feasibility of adopting technologies developed under the program at Department facilities is addressed in Section II.F.

In this section, we address specific aspects that are important to evolving and integrating capabilities of the U.S. electric grid, charging systems, and EVs to minimize the impacts on the grid of EV grid loads while maximizing the utility, decarbonization benefits, and value propositions offered by electric vehicles. The evolution of these systems from today's reality to a future where EVs are fully integrated on the grid is shown in Figure II.1 below.

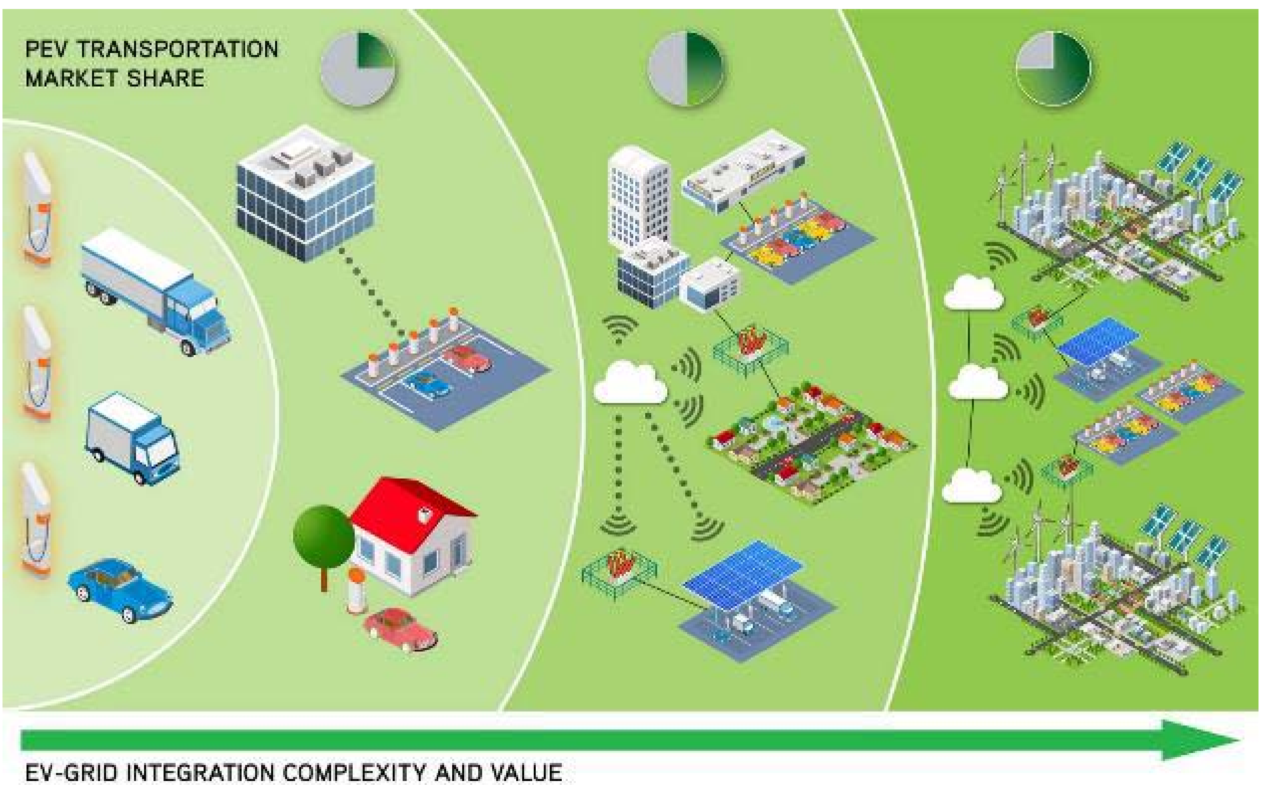


Figure II.26. EV-Grid Evolution - The success of transportation electrification depends on increased grid interaction and optimization for all stakeholders.

A. Evaluation of the Use of Electric Vehicles to Maintain the Reliability of the Electric Grid

EVs offer the potential for storage capabilities and could serve as flexible grid assets that help improve the reliability and resilience of the power system. Directly, or through aggregation services, EVs have the potential to provide grid services like frequency regulation, voltage support, or peak load reduction, as well as supporting black start capabilities on the grid or providing backup power to homes, buildings, or microgrids during a grid disruption. If EVs are not properly integrated with the grid, they could have negative impacts on grid reliability.

Currently, EVs are primarily used by utilities as a flexible load, with passive management approaches such as demand response programs or time-of-use pricing that influence or control vehicle charging (e.g., managed charging). Control is primarily oriented at peak shifting or energy arbitrage. Vehicle charging is incentivized toward periods of lower demand on the power system, reducing the likelihood of overloaded equipment that may lead to a brownout or blackout condition. In areas under grid capacity limitations and/or abnormal load conditions (e.g., heat or freeze wave), the ability to shift this chunk of load can help ensure the reliable operation of the system. However, proper coordination and control of the EV charging to perform this capability is complicated.

With more advanced controls, through active and smart charge management, the use of EVs have been demonstrated in simulation and small-scale demonstration or pilot projects. These include controlling EV charge rates to provide frequency regulation against variable renewable generation like wind or solar[55] [56], or even charge and discharge into the grid to provide these regulation services[57]. Treating bi-directional charging of EVs more similarly to classic energy storage, numerous value streams may become available, especially in light of FERC Order 2222 that enables aggregations of DERs to participate in the wholesale electricity energy market[58]. These not only provide means to improve the reliability and resiliency of the power system, but also can potentially provide value streams to the utility or customer operating the EVs.

Two light-duty vehicle manufacturers now provide EVs with Vehicle to Building (V2B) capability and there are more that are, planning to provide V2B EVs in the near future. This allows the vehicle's battery to be used as a backup power source to a home or business during a major

[55] Kintner-Meyer, Balducci, Jin, Nguyen, Elizondo, Viswanathan, Guo, and Tuffner. 2010. Energy Storage for Power System Applications: A Regional Assessment for the Northwest Power Pool (NWPP). [Online]: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-19300.pdf.

[56] Tuffner, Chassin, Kintner-Meyer, and Gowri. 2012. Utilizing Electric Vehicles to Assist Integration of Large Penetrations of Distributed Photovoltaic Generation. [Online]: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-22064.pdf.

[57] Kempton, Udo, Huber, Komara, Letendre, Baker, Brunner, and Pierre. 2009. A Test of Vehicle-to-Grid (V2G) for Energy Storage and Frequency Regulation in the PJM System. [Online]: https://www1.udel.edu/V2G/resources/test-v2g-in-pjm-jan09.pdf.

[58] US FERC (United States Federal Energy Regulatory Commission). 2021. Participation of Distributed Energy Resources in Markets Operated by Regional Transmission Organizations and Independent System Operators. Docket RM18-9-000, Order 2222. Washington, DC. [Online]: https://www.ferc.gov/sites/default/files/2020-09/E-1_0.pdf.

outage or during events such as public power safety events[59]. These do not directly improve the reliability or resiliency of the larger grid; however, they do provide a backup mechanism for customers and critical facilities, thus improving the customer power reliability and overall resiliency to outage conditions at the individual level.

Challenges/Needs

A significant challenge to using EVs to improve grid resilience and reliability stems from the very nature of their capabilities: they are vehicles/transportation first. As significant portions of the vehicle fleet transition to electrified transportation, that primary use may even override customers' interest or desire to provide grid services. Depending on the use case, electric vehicles may have long dwell times at a charger, incentivizing their use to provide grid services for reliability and resiliency. However, while using an electric vehicle as a battery backup or balancing device to the grid can certainly be helpful for overall reliability and resilience, there may be a greater need for it to serve as a vehicle to evacuate the customer from the affected area. While this will prevent their usage for grid services, it may also be reducing the immediate load as they travel to less impacted areas of the grid/country. However, some fleet owners may deliberately acquire electric vehicles for both transport and energy services (e.g., to monetize V2G or take advantage of V2B and provide peak shaving). To what extent this will happen is unclear and may vary depending on the conditions and energy markets in a given region. Studies are likely needed to evaluate at what point the electrified transportation resources are no longer available to the grid while they perform their primary role as transportation.

V2G, or bi-directional charging, has great potential to provide grid services to maintain electric grid reliability. V2G gets a more direct treatment in Section II.C.vi, but both bi-directional and unidirectional (traditional) charging may have challenges in their use for maintaining grid reliability. The use of EVs, either V1G or V2G to provide grid services will likely require standardization of communications and controls that do not exist today and could potentially increase the costs of EVSE and interconnection to the grid. The revenue stream for these services has potential ownership/stakeholder issues with how to determine pricing for the service, from the aggregator value to any utility fees to what the end customer receives for using their vehicle in this manner. Regulatory frameworks need to be developed and examined to ensure not only fair market approaches to this problem, and to properly evaluate how the revenue streams for both personal use (LDV) and commercial (LDV/MDV/HDV) customers change across electrification scenarios.

With many of the advanced VGI capabilities mentioned, there is an increased need for communications and controls of the different EVs. This could create a large surface for either cyber intrusions, or a large asset pool for potential cyberattacks, which is discussed in greater detail in Section II.E. The ability to control and properly leverage the EV fleet for grid reliability and resilience is certainly warranted but will need to be balanced against overall cybersecurity

[59] CEC (California Energy Commission) 2021. Staff Workshop – Vehicle-to-Building(V2B) for Resilient Backup Power. [Online]: https://www.energy.ca.gov/event/workshop/2021-01/staff-workshop-vehicle-building-v2b-resilient-backup-power.

concerns. Given the long, complicated supply chains for a typical car, this can even include examining supply chain assurances and “dependent technology” considerations[60].

Opportunities

While EVs represent a significant increase in load on the system, which may impact reliability, they also have the potential to help mitigate their impact on the electric grid. The potentially long idle intervals of EVs, coupled with their energy storage capabilities, provide many potential grid service and reliability improving capabilities. A simple “do no harm” approach not only ignores a lot of the potential of EVs, but also ignores other DER technologies developing and influencing the grid.

Electric vehicles are one resource in an increasing field of customer-owned active devices on the grid that can provide additional services and benefits to the electric grid. As the EV population increases, so are technologies such as local energy storage and rooftop photovoltaic (PV) systems. These technologies may have complementary capabilities to help improve their overall integration and usefulness (e.g., rooftop PV and local energy storage). A DER-oriented framework to consistently manage these devices, from defining capabilities and to the actual device interface, will be important for interoperability of various devices, as well as coordinating their interaction with the larger power grid to maintain reliability. Federal agencies, such as DOE and NIST, can partner with industry to build this framework and help not only integrate these new grid resources, but also help ensure it is done in a manner that maintains existing grid reliability.

Coupled with the DER framework and other emerging capabilities, the integration of EVs into the electric grid represents an opportunity to reexamine the metrics for reliability. In addition, the inability of EVs to charge could have negative national economic impacts, which should be factored into reliability metrics. Existing reliability metrics are oriented around customers being merely passive energy takers, not active participants, or energy producers. Significant deployments of EVs (and other DERs) may reveal new ways to quantify reliability of the power system beyond outages and durations[61], with opportunities to tie into efforts defining resiliency, such as GMLC 1.1[62]. When an EV is being used to provide grid services, complementary metrics on the impacts to their transportation capabilities may need evaluation (a sector coupled reliability/resilience metric). Standards bodies (e.g., IEEE, IEC, ANSI, SAE), along with insights from relevant Federal agencies (e.g., DOE, FERC) and private industries (e.g., EPRI, utilities/system operators) can collaborate to define these metrics to quantify the operations of the evolving, more-customer-interactive power system.

[60] CISA (Cybersecurity & Infrastructure Security Agency) 2020, Advanced Persistent Threat Compromise of Government Agencies, Critical Infrastructure, and Private Sector Organizations. [Online]: https://us-cert.cisa.gov/ncas/alerts/aa20-352a.
[61] IEEE (Institute of Electrical and Electronics Engineers). 2013. IEEE Standard 1366-2012 – IEEE Guide for Electric Power Distribution Reliability Indices. [Online]: https://ieeexplore.ieee.org/document/6209381.
[62] GMLC (Grid Modernization Laboratory Consortium) 2020. Grid Modernization: Metrics Analysis (GMLC 1.1). [Online]: https://gmlc.doe.gov/sites/default/files/resources/GMLC1.1_Vol1_Executive_Summary_ackn_draft.pdf.

Takeaways

- EVs are transportation devices first. While they often have significant idle time, especially in residential settings, their availability for grid-reliability-improving services may not be available when needed.
- Advanced EV charging controls have been developed to help provide grid services that improve reliability but have only been evaluated in simulation or small-scale demonstrations in the United States.
- Vehicle manufacturers are starting to have more V2B offerings, allowing the customers to use them for backup power to improve their reliability (See Section II.C.vi for details).
- The reliability cost-to-benefit ratios of EV grid services are still relatively high, due to limited deployments and the novelty of the technology.
- Many of the advanced EV controls to improve reliability will require more communications and aggregation of the EVs, opening up new cybersecurity scenarios and unveiling a new attack plane/vector (See II.E for details).
- EVs are complicated devices, with many components and supply streams. If they become a significant resource for maintaining grid reliability, supply chain assurances (both in availability and cyber-physical considerations) may need to be evaluated (See Section II.E for details).

Recommendations

- DOE could expand activities to coordinate with and support Industry efforts to enable the leveraging of EVs in an overall DER framework. In support of this activity, DOE could quantify and qualify the benefits of EVs to support grid reliability.
- EVs and other DERs will probably require new reliability metrics to be developed. DOE and private entities could expand activities to cooperatively investigate new reliability metrics to capture the impacts of customer-provided and novel technology DER services, including those from EVs.
- Adoption of EVs@Scale and adoption of VGI capabilities may reduce costs of reliability services due to economies of scale. DOE could expand activities to perform demonstrations to valuate and enable adoption of these capabilities.

i. Use of electric vehicles for demand response, load shaping, emergency power, and frequency regulation

This section addresses EV-grid integration capabilities to use electric vehicles for demand response, load shaping, emergency power, and frequency regulation grid services. While EVs can be used to support the grid, an electric vehicle’s primary purpose is mobility. Ultimately, the owner will determine how to deploy its capabilities (as transportation or DER). These services may provide additional benefits to EV ownership based on the possibilities at the vehicle to grid boundary.

Grid services have previously been provided by large, synchronous generators, but technological and market innovations are enabling DERs, like EVs, to provide some of these grid services in a cost-effective manner. Electric vehicles have the potential to be an aggregated resource within the grid services markets. In Section I.B of the report, a description is provided of the various grid services at both the transmission and distribution levels. Medium- and heavy-duty EVs can be aggregated to a magnitude where they can meet not only distribution level but also transmission level grid needs. EVs and EVSEs, when connected and communicating with the grid via standard protocols, have the capability to provide demand response, load shaping, emergency power, and frequency regulation. EVs and EVSEs can provide grid services using either V1G or V2G.

EVs can provide the grid services described below to support grid resilience and reliability. Utilizing these capabilities depends on the availability of the vehicle (Section II.C.ii), the existence of incentives (Section II.C.v), and the implementation of enabling technologies. These enabling technologies include SCM (Section II.C.ii and II.C.vii) and bi-directional power flow (Section II.C.vi). Further discussions of each can be found in the referenced sections.

Demand Response

Demand response is simply complying with a request from the grid to curtail electricity usage. EVs have the capability to reduce and/or stop charging in response to signals (e.g., demand response signals). There are multiple utility programs in the United States that are currently utilizing EVs for demand response services. These programs are being performed by either directly utility control or third-party aggregators. For example, a fleet of EVs using V1G can receive a demand response and choose to defer charging. This type of transaction would be equivalent to providing the following DER grid services (see Section I.B.iii.c for details): Energy Scheduling Service and Reserve Service.

Load Shaping

Load shaping refers to modifying the system loads to a time and location to better align with generation, transmission, and distribution constraints. The load is shifted to a time when the supply and load are better aligned. EVs have the unique capabilities to provide grid shaping because of their on-board energy storage. In its simplest form, EVs can provide load shaping through V1G, similar to demand response, but may involve more nuanced controls and a better understanding of the EVs needs. V2G capable EVs provide the additional benefit of injecting power back to the grid in addition to shedding load. For example, all EVs connected to an EVSE mid-day when solar energy is inexpensive and plentiful could opt to charge if signaled to do so.[63] A V2G capable vehicle could then discharge back to the grid later in the day during high load periods. This grid service can significantly benefit assimilation of renewable energy, reducing ramp requirements, reducing electricity, and charging costs. The DER services (from Section I.B) this provides include Energy Schedule Service and Reserve Service but will have a

[63] The Smart VGI project has shown that an EVSE can be controlled to take advantage of behind the meter solar power and shape the load that is demanded at the building meter/grid interface.

more nuanced control (and different aggregation) compared to the simple demand response call outlined above.

Emergency Power

Emergency power is defined as when the grid is unable to provide electricity to a home or building. Not all EVs can provide emergency power. This grid service requires bi-directional power flow by the EV and bi-directional capable EVSE. In these instances, the vehicle is not just turning charging on or off, but it is sending power to the home (V2H), building (V2B), or load (V2L). Utilizing this capability further requires that the electric service that the vehicle is connected to, on the customer side of the meter, can ensure proper operations and safety while in emergency power mode. This emergency power capability is not considered a grid service, but nonetheless benefits utilities.

Examples of EVs with emergency power capability include the Ford F150 Lightning and the Nissan Leaf.

Frequency Regulation

Frequency Regulation is also known among some utilities as Frequency Response. This is the provision of capacity from interconnected operations services (IOS) resources that deploy automatically to stabilize frequency following a significant and sustained frequency deviation on the interconnection. This grid service detects frequency deviation and instantly injects (or absorbs) active power to help arrest the frequency drop (or increase). DOE's Argonne National Laboratory (ANL) has demonstrated that concurrent charging of a small fleet of electric vehicles can be controlled (i.e., V1G) to match the PJM Regulation Down (D) signal. "PJM Interconnection is a regional transmission organization (RTO) that coordinates the movement of wholesale electricity."[64] "The Regulation D signal is a fast, dynamic signal that requires resources to respond almost instantaneously."[65]

To perform optimized frequency regulation service additional capabilities (e.g., SCM, DERMS, high-speed communications and response) are required (see Section II.C.vii). Not all EVs and/or EVSEE on the market today can perform frequency regulation services.

This type of transaction would be equivalent to providing the following DER grid services: Regulation Service and Frequency Response Service (depending on the complexity of the implementation).

Takeaways

EVs have the capability to provide various grid services that support grid reliability.

While EVs can be used to support the grid, an electric vehicle's primary purpose is mobility. Ultimately the owner will determine how to deploy its capabilities (as transportation or DER).

[64] *Who we are*. PJM©. (n.d.). Retrieved October 15, 2021, from https://www.pjm.com/about-pjm/who-we-are.
[65] *Regulation market*. PJM Learning Center - Regulation Market. (n.d.). Retrieved October 15, 2021, from https://learn.pjm.com/three-priorities/buying-and-selling-energy/ancillary-servicesmarket/regulationmarket.aspx.

- EVs providing grid services will depend on the availability of the vehicle (Section II.C.ii), the existence of incentives (Section II.C.v), and the implementation of enabling technologies.
- Certain grid services will require other technologies, such as controllable V1G or V2X-enabled EVSE, SCM, or DERMs.

Recommendations

DOE could expand activities to conduct RDD&D on furthering and optimizing the capability of EVs and EVSE to provide grid services and accelerate market adoption.

ii. The potential for the reuse of spent electric vehicle batteries for stationary grid storage

Vision for EV-Grid Integrated Future

One vision of the EV-grid future features used, refurbished ("second-life") EV battery packs as stationary grid storage. Once EV battery packs have degraded to 70-80% of their original capacity, they have reached their end of life (EOL) for vehicle applications and are then retired from vehicular use. Proponents of reusing spent EV batteries for stationary grid storage cite the potential to extend the useful life of battery packs while providing lower cost storage for stationary DER grid services. In theory, extending the useful life of the battery pack by several years would increase the salvage value of the pack at the end of its on-board service phase. A few of the many applications for these second life energy storage systems (2^{nd} Life ESS) include stationary energy storage for PV, wind, emergency power, and light rail applications.

A 2015 NREL study concluded the following regarding the potential of second use batteries:

> "The most promising application identified for second use batteries is to replace grid-connected combustion turbine peaker plants and provide peak-shaving services. In comparison to automotive service, use in this application will entail relatively benign duty cycles, generally much less than one cycle per day with discharge durations of greater than 1 hour. Under these conditions, it is anticipated that second use battery lifetimes will be on the order of 10 years. While the value to the original automotive battery owner is restricted primarily to the elimination of end of service costs (battery extraction, disposal, recycling, etc.), the value to the broader community could be significant: decreased cost of peaker plant operation on the order of 10% to 20%, reduction of greenhouse gas emissions and fossil fuel consumption, and deferral of battery recycling."[66]

Peaker plants are often located in or near underserved communities. Minimizing the use of these plants would have significant benefits for the residents of these communities.

[66] J. Neubauer, K. Smith, E. Wood, and A. Pesaran, Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries, Technical Report NREL/TP-5400-63332 February 2015. (Available at URL: http://www.osti.gov/scitech).

When these 2nd Life ESS packs have degraded to the point that they are no longer suitable for stationary grid storage, they would be sent to a battery recycling facility. The recycling facility would process the pack's cells to reclaim the elements for future use. This vision for the future would be a major change from current practices where after being removed from the EV, most of the spent battery packs are immediately processed for disposal or sent to recycling facilities.

Barriers for 2nd Life ESS

The major barriers for these 2nd Life ESS include delivered capability costs factors and price competition from 1st Life ESS. A major barrier for realizing the potential of using spent EV packs for stationary grid storage is that systems based on new batteries have better cost-benefit characteristics than reused EV pack systems. ESS systems composed of new batteries are reliable and the cells come with manufacturer warranties.

The high cost of stationary storage that reuses spent battery packs is due to the following system cost factors:

- UL 1973 and UL 1974 Requirements present significant costs[67]
  - UL 1973-This standard evaluates the battery system's ability to safely withstand simulated abuse conditions. This standard evaluates the system based upon the manufacturer's specified charge and discharge parameters.
  - UL 1974- This standard covers the sorting and grading process of battery packs, modules, cells, and electrochemical capacitors that were originally configured and used for other purposes, such as electric vehicle propulsion, and that are intended for a repurposed use application, such as for use in energy storage systems and other applications for battery packs, modules, cells, and electrochemical capacitors.
- The expense of handling and transporting used batteries which are classified as hazardous materials.
- High uncertainty regarding reliability of 2nd Life ESS.
- One set of uncertainty reliability factors are due to limited information on upstream pack usage history and health status of the pack.
- Another source of uncertainty-based costs is the lack of performance data for battery packs used in 2nd Life ESS systems. There exists the need to collect additional data to validate useful life and cost effectiveness of 2nd Life ESS. A 2015 study indicated that technician labor is a major cost element of repurposing operations that must be minimized. As such, it is economically impractical to replace faulty cells within modules, and thus minimizing purchases of modules containing faulty cells is critical. Use of vehicle

[67] Ben Lyon, Repurpose Energy LLC, RePurpose Energy presentation on 2nd Life ESS during EPRI webinar on Circular Economies, March 22, 2021. (URL: https://www.repurpose.energy)

diagnostics data to support used battery purchases is therefore of great value to repurposers[68].

The costs associated with cooling the packs. Many EV packs require active control of the operating temperatures. Once removed from the EV, the pack loses its cooling systems. 2nd Life ESS systems may need to provide cooling systems for the packs which adds to the system costs.

Price Competition from 1st Life ESS systems

Falling prices for new Li batteries are a challenge for this industry because it reduces the market prices for ESS capabilities[69]

The prices for new stationary batteries that are sold in California are attractive because those new batteries are subsidized by the state. In contrast, incentives/rebates are unavailable for 2nd Life ESS[70]

The lack of life cycle cost-benefit analysis for 2nd Life ESS systems makes an "apples to apples" value comparison between 1st and 2nd Life ESS systems difficult. A 2015 NREL study concluded that "Life cycle analyses that show the overall benefit to society of battery second use strategies are important to demonstrate value that may not be captured in economic calculations"[71].

In addition to the cost barriers, a criticism of reuse of spent EV batteries is that it complicates and delays the recycling of the battery cells. Currently, OEMs are responsible for ensuring that battery packs are properly disposed of or recycled at the end of service. Placing these spent packs into second use application complicates the pack accountability, by including the spent pack vendor, integrated power system provider, and stationary power system owners.

Takeaways

The vision for using spent EV battery packs has merit but faces significant barriers to market viability that must be resolved.

Recommendations

DOE could establish RDD&D projects to develop tools and standard procedures to assess state of health (SOH) at the cell and pack level and predict future battery degradation related to second use applications. The diagnostic capabilities would help the industry address the specific requirements of UL 1974 by assessing the health status of the pack and would predict the reliability of each pack.

[68] J. Neubauer, K. Smith, E. Wood, and A. Pesaran, Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries, Technical Report NREL/TP-5400-63332 February 2015. (Available at URL: http://www.osti.gov/scitech).

[69] Ben Lyon, Repurpose Energy LLC, RePurpose Energy presentation on 2nd Life ESS during EPRI webinar on Circular Economies, March 22, 2021. (URL: https://www.repurpose.energy)

[70] Ben Lyon, Repurpose Energy LLC, RePurpose Energy presentation on 2nd Life ESS during EPRI webinar on Circular Economies, March 22, 2021. (URL: https://www.repurpose.energy)

[71] J. Neubauer, K. Smith, E. Wood, and A. Pesaran, Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries, Technical Report NREL/TP-5400-63332 February 2015. (Available at URL: http://www.osti.gov/scitech)

DOE in cooperation with industry stakeholders could conduct RD&D to mitigate factors that cause thermal runaway in battery packs in transit, which will improve public safety and minimize transportation costs of spent packs.

DOE could support industry in developing methodologies to establish a historical record of on-board usage by collecting data on pack operations and operating environments. DOE could also play a critical role to encourage industry to create a standard EV battery pack usage data set and open interface protocols to access the usage history for any given battery pack.

DOE could conduct a study working with industry to evaluate and quantify thermal management needs associated with secondary use of spent EV batteries for stationary storage applications.

B. Evaluation of the Impact of Grid Integration on Electric Vehicles

With advanced control and proper management, EVs can be used as flexible grid assets and participate in several grid services such as frequency regulation, peak reduction, supporting black start capabilities, and backup power support during blackouts. Vehicle manufacturers are beginning to offer more vehicle to everything, commonly referred to as V2X, which includes home (V2H), building (V2B), load (V2L), grid (V2G) capabilities, allowing EVs to participate in more revenue streams during idle hours. DOE has studied the impact of bi-directional power flow on EV batteries and the implication of participation in grid services on EV warranties. The results of each are presented in the following sections.

i. The impact of bi-directional electricity flow on battery degradation

Bi-directional electricity flow is a key enabling technology allowing EVs to participate in V2X activities. While the ability to participate in multiple revenue services can potentially increase EV adoption in all vehicle segments (light-, medium-, heavy-duty), the additional use due to V2X participation will result in additional battery degradation as well. It is important to understand how EV batteries degrade due to V2X participation and specifically, what levels of degradation occur since the economic viability of V2X is primarily dependent on battery degradation[72].

EV batteries can degrade in two ways:

a) **capacity fade** resulting in a reduction in the available energy storage capability of the pack and hence, **a reduction in the driving range;**
b) **power fade** resulting in a reduction in the available discharge or charge power, reducing acceleration and regenerative braking and hence**, a reduction in efficiency.**

[72] Kotub Uddin, Matthieu Dubarry, and Mark B. Glick, "The viability of vehicle-to-grid operations from a battery technology and policy perspective", Energy Policy 113 (2018) 342–347.

These fades occur both while the vehicle battery is being used or is idle, albeit with different intensities and rates. The underlying mechanisms that cause degradation depend on a variety of factors including, but not limited to, temperature, depth of discharge (DOD), state of charge (SOC), charging/discharging C-rate, battery chemistry, and energy throughput. Controlled tests can be performed to understand and quantify the impact of each of these factors on the overall degradation. One such case study has been performed where two plug-in hybrid electric vehicle (PHEV) battery packs are tested to evaluate the additional degradation caused by V2G participation. This section will detail key findings from this project to provide insight into these factors on battery degradation and the open literature to establish current state and research avenues.

Case Study Results

As part of a DOE-funded project led by EPRI to develop a bi-directional Level 1 DC charger for residential use, NREL was tasked with studying the degradation impact on traction batteries when used in vehicle to grid applications. Under this project, two PHEV battery packs are tested to identify the impact of V2G cycles on battery degradation. These battery packs, each with an energy capacity of 16 kWh and graphite/Lithium nickel manganese cobalt (NMC) oxide chemistries, are cycled round the clock with selected drive cycles and additional discharge of the V2X pack. Figure II.2 shows a comparison of the power profiles encountered by the battery packs in the baseline and V2X cases, while steps of the overall profile are presented in Table II.1. Both of these profiles constitute driving to work, charging at work, and driving back home. The driving includes two drive cycles, a low-speed[73] and a high-speed driving cycle[74], to emulate both city and highway driving, covering 15.45 miles and a total energy throughput of 9.22 kWh one way. At home, the baseline pack is charged to 95% SOC but the V2X pack is discharged (at constant power) to 25% SOC before charging back to 95% SOC. It should be noted that the constant V2G discharge power of 10 kW is significant for a battery pack with a capacity of 16 kWh. Impact of calendar degradation (capacity fade during idle time) is eliminated by removing the 18 hours of non-operational time for both the battery packs.

[73] The city cycle is the U.S. Environmental Protection Agency (EPA)'s Urban Dynamometer Driving Schedule.
[74] The Supplemental Federal Test Procedure is a high acceleration aggressive driving schedule often known as US06.

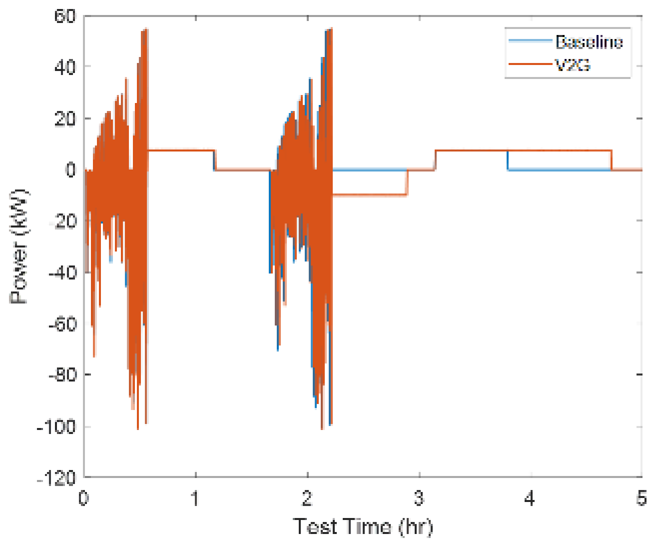
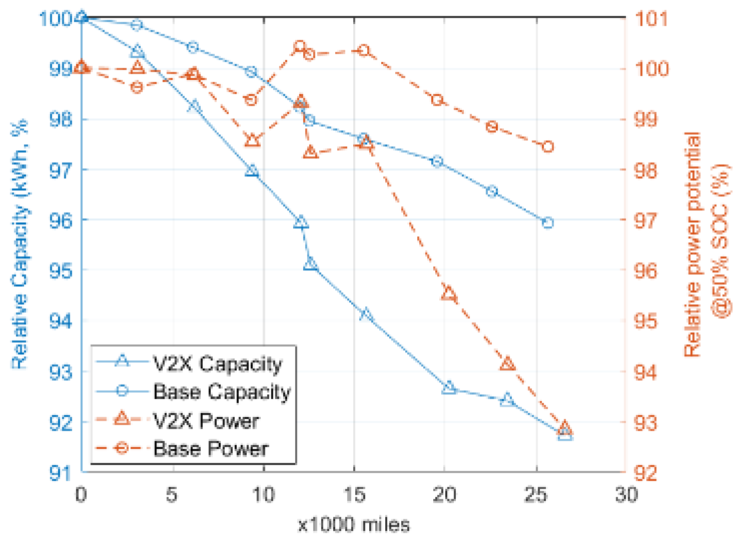


Figure II.27. Comparison of the baseline and V2G power profile.

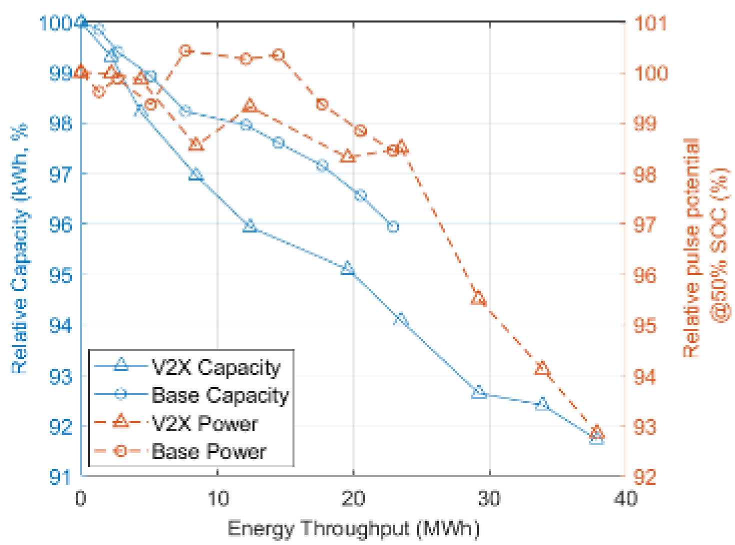
Table II.2. Cycling steps for the V2G and baseline battery packs.

Segments of the cycling profile	Pack 1 (V2G)	Pack 2 (Baseline)
	Time, hours	
Drive to work	0.5	0.5
Charge (70% to 95%)	1	1
Wait	0.5	0.5
Work	-	-
Drive home	0.5	0.5
Discharge at home (10kW)	25% SOC	0
Charge to 95%	2	1
Wait (key cycle – contactor open)	1	3
Total time/cycle	6	6

Reference performance tests (RPTs) are run after every 28 days to estimate the capacity (and resistance) of the pack, which provide a direct comparison of the resultant degradation due to V2X cycling compared to "business-as-usual" baseline use of PHEV batteries. RPT tests consist of a cycling test to measure capacity at a rate of C/3 spanning 100% to 0% SOC and a hybrid pulse power characterization (HPPC) test to measure resistance spanning 100% to 0% SOC. Figure II.3 summarizes the additional degradation caused by bi-directional electricity flow from V2X participation.



(a) Relative capacity and pulse power capability of both the battery packs show degradation with respect to driving miles. The V2X profile has an additional ~4% capacity degradation and ~5% power degradation over ~26,000 miles of driving compared to the baseline profile.



(b) Relative capacity and pulse power capability shown as a function of energy throughput. For the same throughput, the V2X cycle is shown to cause more degradation (more so for capacity) than the baseline case.

Figure II.28. Resultant degradation in battery packs from V2G and baseline cycles.

Some key aspects of this case study, specific to this V2X cycle, can be summarized as follows:

1. Temperature is very tightly controlled between the two battery packs such that temperature difference between them is in the order of 1-2°C. In this way, the impact of differences in temperature on the battery packs is eliminated. This mimics a well-controlled thermal system that minimizes the thermal impact of the V2X use.
2. The battery pack participating in V2X experiences more energy throughput due to the V2X step, which causes additional degradation. However, it should be noted that the amount of degradation seen here corresponds to a very high discharge (C-rate of >C/2), which is significant. Degradation may be reduced if V2X demand is at lower discharge power (C-rates),

3. The baseline cycle results in a DOD of ~25% but the DOD caused by V2X use in this project is ~70% over a cycle. Higher DOD is another factor causing additional degradation in the V2X pack.

The results of this study are dependent on the specific cycle identified, which includes high-discharge daily V2X activities. These results are not indicative of degradation under different V2X cycles.

Literature Insights

Several studies have investigated various aspects of bi-directional power flow in Li-ion batteries for emulating V2X applications. While V2X applications cause additional degradation in Li-ion batteries, a key take way from several studies is that the amount of additional degradation depends on the underlying V2X scenario.

Dubarry et al. (2017)[75] conducted design of experiments-based degradation tests on 100 Panasonic 3.35 Amp-hour (Ah) graphite/Lithium Nickel Cobalt Aluminum Oxide (NCA) batteries emulating V2G and grid to vehicle (G2V) operations. Their prognosis of a 25-kWh battery pack shows that participating in V2G, even once a day at constant power, can make the battery lose more than 20% capacity after 5 years. However, the authors acknowledge the limitations of their prognosis in that it assumes modeled degradation mechanisms to be consistent throughout and does not include certain mechanisms such as break-in mechanism or accelerated degradation that can increase capacity and drastically increase the rate of degradation.

In contrast, Uddin et al. (2018)[76] shows that using an optimal algorithm that actively minimizes battery degradation during V2G activities, capacity fade and power fade can be achieved that is lower in magnitude to a situation where the EVs do not participate in V2G activities. The authors use battery degradation models for NCA chemistry cells to identify regimes of operation of the battery that result in less degradation. For example, if participating in V2G allows the battery to move from an SOC value of higher degradation to lower degradation, then the algorithm allows the EV to participate in V2G. Simulation of 120 EVs using this algorithm to perform load levelling of a commercial building shows that by allowing participation of some EVs in V2G activities, the algorithm reduces capacity fade by up to 9.1% (~1.8% in relative capacity) and power fade by up to 12.1% (~12% in relative resistance) compared to the baseline case without V2G.

[75] Matthieu Dubarry, Arnaud Devie, and Katherine McKenzie, "Durability and reliability of electric vehicle batteries under electric utility grid operations: Bidirectional charging impact analysis", Journal of Power Sources 358 (2017) 39-49.

[76] Kotub Uddin, Tim Jackson, Widanalage D. Widanage, Gael Chouchelamane, Paul A. Jennings, James Marco, "On the possibility of extending the lifetime of lithium-ion batteries through optimal V2G facilitated by an integrated vehicle and smart-grid system", Energy 133 (2017) 710-722.

Darcovich et al. (2017)[77] used an electrochemical model and a capacity fade model of a lithium NMC chemistry cell to simulate the degradation in a battery pack for a Battery Electric Vehicle with a range of 120 miles (BEV120) of 28 kWh energy capacity participating in V2H activities. Their results show that degradation is dependent on the duration of V2H activity as well as the time of participation as that dictates the severity of V2H demands. Simulations show that the considered BEV120 battery pack will have a service life (before reaching 75% of initial capacity) of 10.5 years with a daily 50 km driving range. However, addition of a daily 8-hour V2H event to this baseline usage resulted in a decrease in the battery service life by 1.9 years.

Battery degradation due to V2G participation is multi-faceted, which makes it very difficult to analyze and quantify. One such key aspect is the dependence of V2G incurred degradation on the battery chemistry. Petit et al. (2016)[78] investigated the degradation impact of V2G participation on graphite lithium iron phosphate (LFP) (A123s 2.3 Ah) and graphite/NCA (Saft VL6P 7 Ah) chemistries. Both the calendar and cycling aging rates are found to be higher for the LFP chemistry compared to the NCA, which result in a higher degradation in the former (~6% capacity loss over a year for LFP compared to ~4% for NCA from nominal usage). However, calendar degradation is comparable to cycling degradation in the LFP chemistry, resulting in degradation from strong V2G participation (3 times a day) to be similar in magnitude to that from nominal case with high storage SOC (90% SOC). For the NCA chemistry, a strong V2G use results in an additional 1.5% capacity loss in a year compared to nominal case with high storage SOC.

A study on school bus electrification investigates battery degradation under different use case scenarios including smart V2B electricity flow[79]. The study uses a techno-economic optimization tool[80] to optimize the battery charging and dispatch for V2B and battery life analysis models[81] to analyze the resultant degradation for a 10-year period. With proper thermal management, school buses due to their moderate duty cycles may be ideal candidates for V2B participation. All four of the investigated battery technologies (one LFP, one NCA, and two NMC chemistries) except LFP exhibited more than 8 years of operation before their capacity degraded below 80% of the initial capacity. The investigated NCA and LFP technologies showed lower degradation during V2B than baseline because V2B resulted in a lower average SOC in this work and these chemistries are more sensitive to average SOC. Thus, V2B improves degradation by ~0-4% for these technologies over 10 years. However, the investigated two NMC technologies showed

[77] Ken Darcovich, Steven Recoskie, Hajo Ribberink, Fleurine Pincet, Amaury Foissac, “Effect on battery life of vehicle-to-home electric power provision under Canadian residential electrical demand”, Applied Thermal Engineering 114 (2017) 1515-1522.

[78] Martin Petit, Eric Prada, Valérie Sauvant-Moynot, “Development of an empirical aging model for Li-ion batteries and application to assess the impact of Vehicle-to-Grid strategies on battery lifetime”, Applied Energy 172 (2016) 398-407.

[79] W. Becker, E. Miller, P. P. Mishra, R. Jain, D. Olis and X. Li, "Cost Reduction of School Bus Fleet Electrification With Optimized Charging and Distributed Energy Resources”, 2019 North American Power Symposium (NAPS), 2019, pp. 1-6.

[80] D. Cutler, D. Olis, E. Elgqvist, X. Li, N. Laws, N. DiOrio, et al., Reopt: A platform for energy system integration and optimization, 2017, [online] Available: https://reopt.nrel.gov/. Accessed June 2021..

[81] K. Smith, A. Saxon, M. Keyser, B. Lundstrom, Ziwei Cao and A. Roc, "Life prediction model for grid-connected li-ion battery energy storage system", 2017 American Control Conference (ACC), pp. 4062-4068, May 2017.

higher degradation during V2B than baseline because V2B resulted in a higher maximum DOD in this work and these NMC chemistries are more sensitive to maximum DOD, although the NMC chemistries retain more than 80% capacity at the end of 10 years. Thus, V2B increases degradation by ~1-11% for the NMC chemistries over 10 years.

In Wang et al. (2016)[82], the authors compared the degradation caused by multiple grid services to that from normal driving using a detailed powertrain model and a battery degradation model for NMC chemistry. Their simulations show that even in the extreme case where grid services are provided every day for 10 years between 7:00-9:00 PM, increase in capacity loss from the base driving and uncontrolled charging case is 3.62% and 5.6% for frequency regulation and peak load shaving, respectively. In a more realistic scenario where grid services are provided 20 times per year, average additional capacity losses over a 10-year service life from such services are 0.38%, 0.21%, and 1.18% for peak load shaving, frequency regulation, and net load shaping, respectively.

Takeaways

The impact of V2X participation on battery degradation depends on several factors such as battery chemistry, temperature impacts, depth of discharge, discharge rates, and additional energy throughput.

- Battery degradation is impacted by both the use case for V2X and the vehicle utilization. There will not be a single result for whether V2X degradation is either negligible or significant.
- There is great uncertainty of the potential impacts of V2X on the traction batteries and more independent testing and data are needed before vehicle manufacturers will make bi-directional operation widely available.

Recommendations

- DOE could conduct further studies of the degradation impact on batteries under various V2X operations to develop confidence in the capabilities of EVs to provide V2X services.
- DOE could develop cell chemistry design approaches that will minimize impacts of V2X operations on EV batteries.
- DOE working with industry stakeholders could develop models and tools, such as machine learning and artificial intelligence, to accurately estimate degradation for specific use cases and predict the value of V2X participation.
- Vehicle manufacturers could develop and deploy intelligent controls for EVs that are designed for one or more use cases and can balance the degradation effects of additional cycling due to V2X for different battery technologies. These technologies could play a critical role in alleviating consumer and manufacturer warranty concerns.

[82] Dai Wang, Jonathan Coignard, Teng Zeng, Cong Zhang, and Samveg Saxena, "Quantifying electric vehicle battery degradation from driving vs. vehicle-to-grid services", Journal of Power Sources 332 (2016) 193-203.

ii. The implications of the use of electric vehicles for grid services on original equipment manufacturer warranties

The EV-grid integrated future has EVs providing a broad range of grid services such as load management, DER utilization, and bi-directional power, via an integrated system of grid, EVSE, and vehicle capabilities.

Several of the EV grid services use V1G methods to shape and optimize the charging load that the grid must support. Other services will use V2X methods to provide back-fed power to provide emergency and ad-hoc grid support. Inherent in both types of services is the requirement that those operations provide net value to both the grid operators and the EV owners. One part of that requirement is that the exercise of grid services does not have detrimental effects on the grid, EVSE, and vehicle systems. To meet these requirements, the grid services equipment must be designed and tested to ensure that operations do not undermine the economics of the warranties that protect the monetary interests of the vehicle, EVSE, and grid owners.

Currently, there are no prohibitions on EVs participating in V1G grid services by EV OEMs. There are two EV OEMs that currently allow V2X operations under warranty for specific models they sell and specific applications. There are several other EV OEMs that have recently announced plans for their EVs to perform V2X functions.

In the past and currently, several EV OEMs have indicated that if their EV is used for V2X it would nullify the vehicle warranty. The EV OEMs asserted that studies showed that V2X operations degraded the EV battery pack and therefore would shorten the life of the pack. A battery pack that has been degraded is more likely to result in a dissatisfied EV owner, a costly warranty replacement claim (to the EV OEM) by the vehicle owner, and a tarnished reputation for the EV brand. The EV OEMs also are motivated to explicitly prohibit V2G operations by their vehicles to decrease the company's liability for injury to people and damaged equipment from aftermarket and experimental V2X applications. A strong motivator to heed that prohibition is invalidation of the vehicle's warranty because of using the vehicle for V2X operations. For several OEMs, the prospect of V2X operations is associated with undermining their vehicle's reliability, the company's business model, and the economic interests of their customers.

Based on EV OEM responses to DOE's "Integrating EVs Onto the Electric Grid" RFI, this issue of EV battery warranties in the EV-Grid integrated future is a major concern, but the capability for EVs to provide grid services is easier to achieve with V1G grid service methods than V2X grid services methods. The OEM RFI responses shown below describe the OEMs' perceived challenges and barriers to maintaining their warranties. V1G grid services provide favorable warranty value propositions while the costs of building EVs capable of providing frequent V2G grid services are problematic and the costs of associated with building EVs that provide infrequent emergency power grid services (V2B/V2H) are less problematic.

Challenges and Barriers

The following is an EV OEM's perspective that highlights the challenges and barriers regarding V2G, V1G, and emergency V2H grid services impacts on EV warranties (excerpt from DOE VGI RFI response):

> *"<u>The impact of using vehicle batteries for grid services on OEM warranties is a major concern.</u> The development of a mechanism to track the usage of the battery that is understandable by the customer and allows OEMs to track the real battery usage while providing grid services is essential to mitigate the warranty impact.*
>
> - *V2G operation creates a lot of challenges that need to be better understood, especially the implications on battery life and value proposition back to the vehicle owner. Many of these electrical grid needs can be realized through V1G by just starting charging and stopping charging in response to grid needs, assuming the EV/PHEV population is large enough. In this case, no export of power is needed. By maximizing the benefit of V1G, it would be possible to:*
>   - *Avoid unnecessary battery charging and discharging power losses of >10%.*
>   - *Avoid unnecessary charger losses of ~10% (round-trip).*
>   - *Avoid unnecessary battery cycling and lifetime degradation.*
>
> *Regarding emergency power to critical load (such as a building or a community), V2H/V2B exporting power would be required. Due to the emergency situation, the implications of exporting power would not be as great a concern since they won't happen as often. However, there is an overhead to the vehicle design and cost to enable this bi-directional power flow capability and how it can directly benefit the owner of the vehicle needs to be studied more."*

As noted by the OEM, it is a challenge to obtain detailed information on the effects of V2X grid services on the battery pack. A barrier to acceptance of V2X grid services is lack of analysis and tools to objectively evaluate the value propositions of V2X from each stakeholder's perspective and the aggregated value proposition of the service

RDD&D Opportunities

DOE does not currently have projects that specifically address the role of warranties in EV-grid integration.

If appropriate, DOE, in cooperation with Industry stakeholders, can develop a strategy to ensure that the challenges and barriers are being addressed to enable the objective valuation and potential impacts of EV grid services. That strategy could incorporate the needs identified by the EV OEM response above (e.g., mechanisms for allowing the customer to track battery usage and the impacts, better understanding of the implications of V2X on battery life). The strategy also could make analyses and technical data available to the public.

DOE could collect data and perform analyses on degradation of batteries due to V2X operations. This data set can be made available to EV OEMs to help inform their product and warranty decisions.

Takeaways

EV warranties are a mechanism used to protect the economic and safety interests of EV owners and EV OEMs. EV-Grid integration stakeholders need to understand the underlying concerns that may cause an EV OEM to nullify the warranty when the EV is used to provide V2X services.

EV-Grid integration needs to address the technologies, tools, and data necessary for developing integrated technologies that are safe, mutually beneficial, and viable.

Recommendations

DOE could work with stakeholders to collect data on the degradation of batteries due to V2X operations in the most likely operating use cases, perform analyses on the data collected, and make the data set and analyses results available to EV OEMs.

C. Study Results on RD&D Opportunities, Challenges, and Standards Needed for Integrating Electric Vehicles onto the Electric Grid

The addition of EVs onto the electric grid represents an increase in overall loading on the system. Typical residential charging today is equivalent to adding an additional electric water heater or larger load to the system, and medium- and heavy-duty vehicle charging represents an even larger load. Numerous studies have explored the overall energy capacity of the grid to host additional electric vehicles[83] , as well as how electric vehicles may be leveraged to provide services to the bulk power system[84, 85]. While there have been several studies on distribution system impacts and operating strategies, the distribution system is significantly more diverse than the transmission system. Aging and insufficient infrastructure is more likely to cause problems at the distribution level as this significant load is added to the system.

When considering EV impacts on the electric grid, it is important to consider both the macro (transmission-level) and micro (distribution-level and neighborhood-level) impacts of the deployment. At the highest level, there needs to be enough power generation to support a higher population of EVs, including LDVs, MDVs, and HDVs. Prior studies have indicated that the power grid typically has enough nameplate capacity (the maximum rated output of a generator)

[83] Kintner-Meyer, Davis, Sridhar, Bhatnagar, Mahserejian, and Ghosal 2020. Electric Vehicles at Scale – Phase I Analysis: High EV Adoption Impacts on the Western U.S. Power Grid. [Online]: https://www.pnnl.gov/sites/default/files/media/file/EV-AT-SCALE_1_IMPACTS_final.pdf.

[84] Kempton, Udo, Huber, Komara, Letendre, Baker, Brunner, and Pearre 2009. A Test of Vehicle-to-Grid (V2G) for Energy Storage and Frequency Regulation in the PJM System. [Online]: https://www1.udel.edu/V2G/resources/test-v2g-in-pjm-jan09.pdf.

[85] Pratt, Duobe, Hovsapian, et al. 2020. Grid Services from DER Device Fleets: Volume 1 – Battery-Equivalent Models of Devices and Fleets. [Online]: https://gmlc.doe.gov/sites/default/files/resources/PNNL-31006%20Grid%20Services%20from%20Device%20-%20Vol%201%20Battery-Equivalent%20Models.pdf

to support an increasing EV fleet[86]. However, conveying the power from the generation plants to the load centers is where many of the capacity constraints become relevant. This is further complicated by seasonal changes in load and generation patterns, which may shift the capacity constraints and congested areas, requiring even more detailed analysis.

Beyond normal charging operations, EVs also have the potential to be leveraged to provide grid services. Many prior studies have explored the benefits EVs can provide to the grid, including providing grid services to help integrate renewable generation on the transmission system. However, this may create competing objectives between transmission and distribution – a service benefiting the transmission system may be causing voltage or overload issues at the distribution level[87]. Analysis of the whole system (both transmission and distribution) is needed to ensure services provided to one portion of the power grid are not doing so at the detriment of another.

While there are many areas that influence the power system capacity (e.g., transient stability of the transmission system), capacity restrictions are more likely to be associated with overloaded equipment. In particular, there may be capacity restrictions in the distribution lines or transformers. Figure II.4 provides a representation of this for different power grid voltage levels (distribution, subtransmission, and transmission) – lower voltage systems are often lower capacity and will have challenges integrating EVs at a lower penetration level. This is further complicated by many of these lower voltage areas typically being located in low-to-middle income areas, where upgrades may not be a priority.

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[86] Kintner-Meyer, Davis, Sridhar, Bhatnagar, Mahserejian, and Ghosal 2020. Electric Vehicles at Scale – Phase I Analysis: High EV Adoption Impacts on the Western U.S. Power Grid. [Online]: https://www.pnnl.gov/sites/default/files/media/file/EV-AT-SCALE_1_IMPACTS_final.pdf.

[87] Tuffner, Chassin, Kintner-Meyer, and Gowri 2012. Utilizing Electric Vehicles to Assist Integration of Large Penetrations of Distributed Photovoltaic Generation. [Online]: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-22064.pdf

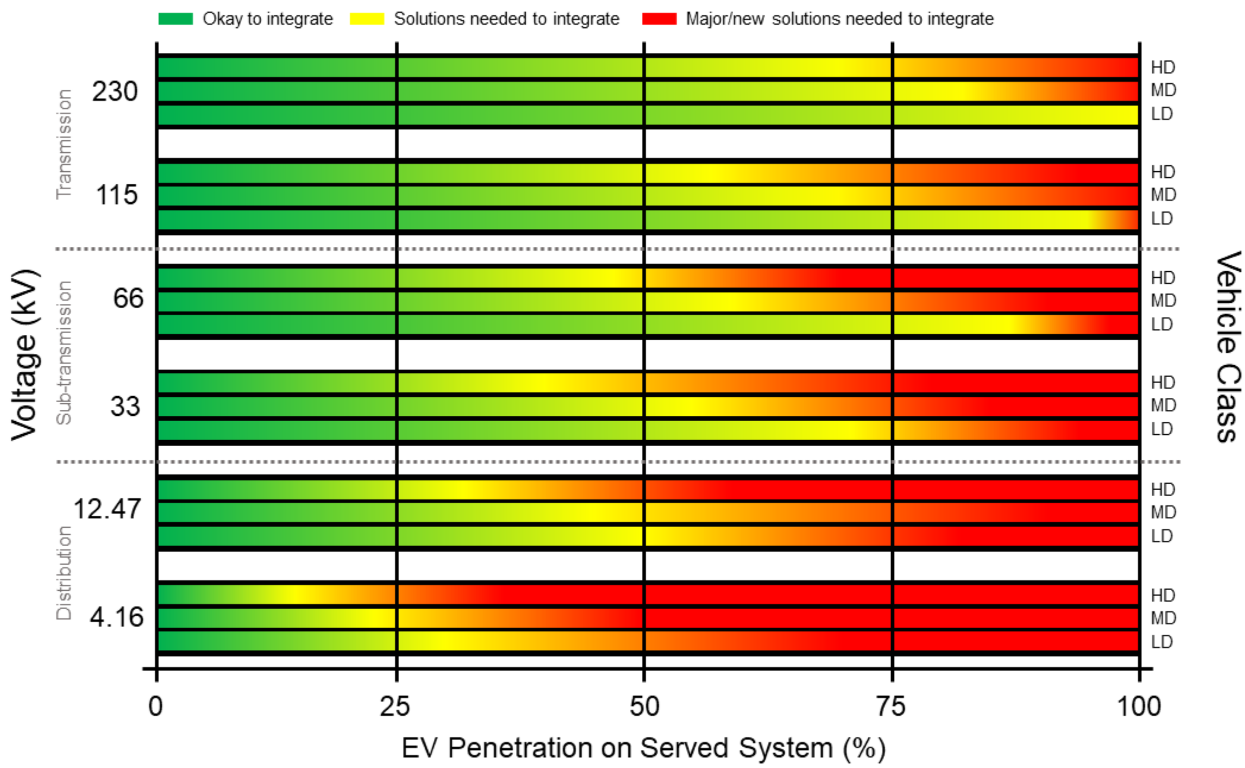

Figure II.29. Impacts of EV penetration for different voltage levels on the electric grid[88],[89],[90].[91],[92].

Takeaways

- The addition of EVs onto the electric grid represents an increase in overall loading on the system.
- Aging and insufficient infrastructure is more likely to cause problems at the distribution level as this significant EV load is added to the system.

[88] Kintner-Meyer, Davis, Sridhar, Bhatnagar, Mahserejian, and Ghosal 2020. Electric Vehicles at Scale – Phase I Analysis: High EV Adoption Impacts on the Western U.S. Power Grid. [Online]: https://www.pnnl.gov/sites/default/files/media/file/EV-AT-SCALE_1_IMPACTS_final.pdf

[89] Southern California Edison Distribution Engineering and Advanced Technology. 2012. The Impact of Localized Energy Resources on Southern California Edison's Transmission and Distribution System. [Online]: https://efiling.energy.ca.gov/GetDocument.aspx?tn=68239

[90] Warwick, Hardy, Hoffman, and Homer. 2016. Electricity Distribution System Baseline Report. Tech Report PNNL-25178. [Online]: https://www.energy.gov/sites/prod/files/2017/01/f34/Electricity%20Distribution%20System%20Baseline%20Report.pdf

[91] U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability. 2016. Distribution Automation - Results from the Smart Grid Investment Grant Program. [Online]: https://www.energy.gov/sites/prod/files/2016/11/f34/Distribution%20Automation%20Summary%20Report_09-29-16.pdf

[92] Meintz, Lave, and Scoffield, 2020. Charging Infrastructure Technologies: Smart Electric Vehicle Charging for a Reliable and Resilient Grid (RECHARGE) – Annual Merit Review Presentation. [Online]: https://www.nrel.gov/docs/fy20osti/76717.pdf

- As the penetration of EVs increases, there is potential for the impacts of the additional devices to create both problems and opportunities at all levels of the power system (distribution, subtransmission, and transmission), which will require more investigation at both the local level and system level.

i. The Distribution Grid Infrastructure Needed to Support an Increase in Charging Capacity

While both the transmission and distribution impacts must be considered for an increased EV fleet, the distribution system is more likely to have serious issues like aging equipment, overloaded lines, or overall power quality issues. Properly anticipating and mitigating these issues on the distribution system will help reduce the issues with an increased EV presence on the power system.

In spite of the prior statement, there are distribution systems with the available capacity and equipment to support the increased load associated with widespread EV adoption. Either through anticipated capital expenditures, or adoption of “non-wires” solutions like demand response, some distribution companies have successfully provided enough margin to support the addition of EVs on their systems[93].

However, there are plenty of utilities that may still have issues. As reflected in Figure II.4 (above), the lower the system voltage, the higher the likelihood of a necessary mitigation on the system to accommodate the increased EV fleet. Many distribution-impact studies are examining higher voltage distribution feeders, typically operating around 15 kV or above. However, there are still numerous utilities or feeders running lower distribution voltages. A survey from 1995 of 107 utilities showed that 68% of them had circuits with voltage below 10 kV[94]. A more recent 2018 survey of 167 utilities showed 35% of those respondents had feeders operating below 10 kV[95]. Feeders operating under 10 kV tend to have more issues with overloading equipment and voltage sags and tend to be older as well. While the two surveys only represent a small fraction of all distribution utilities, it still shows a significant portion of their feeder circuits would be in this more susceptible category. If one takes into account the survey respondents are likely more progressive utilities, involved in research efforts and surveys, the survey sample may be extremely conservative in the percentage of affected feeders in the United States.

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[93] Meintz, Lave, and Scoffield, 2020. Charging Infrastructure Technologies: Smart Electric Vehicle Charging for a Reliable and Resilient Grid (RECHARGE) – Annual Merit Review Presentation. [Online]: https://www.nrel.gov/docs/fy20osti/76717.pdf.

[94] IEEE (Institute of Electrical and Electronics Engineers) Working Group on Distribution Protection 1995. Distribution Line Protection Practices – Industry Survey Results – IEEE PSRC Report in *IEEE Transactions on Power Delivery*, Vol. 10, No 1, January 1995. pg. 176-186. [Online]: https://doi.org/10.1109/61.368400.

[95] APPA (American Public Power Association) 2018. Evaluation of Data Submitted in APPA’s 2018 Distribution System Reliability & Operations Survey. [Online]: https://www.publicpower.org/system/files/documents/2018%20DSRO%20Report_0.pdf.

Challenges/Needs

While there have been numerous studies examining distribution-level impacts of electric vehicles, many of these have been on either IEEE test systems that are overbuilt or significantly more robust than they need to be (a consequence of their initial design being to test power-flow solvers, NOT for use in explicit system studies[96], or on feeders for demonstration projects that are in more affluent neighborhoods or green-field deployments). With large scale electrification of transportation, the EVs will be deployed and potentially charging in all varieties of distribution systems, including those operating lower voltage and legacy equipment. More detailed studies, or mechanisms for smaller utilities to properly evaluate their systems, are needed to help predict and then mitigate distribution-level impacts of the increased EV fleet.

A further challenge is most of the aforementioned studies have focused on residential deployments and the light-duty vehicle fleet. Medium- and heavy-duty vehicle deployments are expected to be quite significant in the future. While these may be smaller deployments in terms of pure numbers, the batteries and electrical load will be significantly larger, potentially exceeding the needs of the LDV fleet. While many such facilities will be connected at the transmission or subtransmission level, some may still be deployed at distribution-level voltages. Regardless, much like the heterogeneous feeder population, studies or a useful mechanism to evaluate individual systems will be needed to help anticipate issues with the large deployment of EVs. One proposed approach is to perform EV impact analysis in a manner similar to the existing analysis for the integration of new solar PV generation on a system. This can include issues like additional harmonics and power quality problems diverse EV fleets may cause while charging, especially in the distribution system where direct measurements of such behaviors are often limited. DOE, through the NREL-led Recharge program, has conducted distribution feeder studies in Atlanta (SNL) and Minneapolis networks, but these were focused on newer feeders (>12kV). As adoption increases and these technologies are adopted and become more available to underserved communities, we will see the gas station model with higher power charging likely causing issues for the distribution system. The gas station model can also impact rural areas with limited grid capacity[97].

In all vehicle fleet scenarios (LDVs, MDVs, and HDVs), the flow of data will represent an additional challenge. Technological concerns, such as increased data flow and a requirement for additional bandwidth, will pose challenges, but are still rooted in a physical constraint and can be resolved with a technology deployment. Section II.C.vii provides detail on details of the data stream, as well as what parties may receive it. A greater challenge with data will be ownership and accessibility to the data, and the legitimate interests of commercial or personal privacy of

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[96] IEEE (Institute of Electrical and Electronics Engineers) Test Feeder Working Group of the Distribution System Analysis Subcommittee 2018. Analytic Considerations and Design Basis for the IEEE Distribution Test Feeders in *IEEE Transactions on Power Systems*, Vol. 33, No 3, May 2018. pg. 3181-3188. [Online}: https://doi.org/10.1109/TPWRS.2017.2760011.

[97] Meintz, Lave, and Scoffield, 2020. Charging Infrastructure Technologies: Smart Electric Vehicle Charging for a Reliable and Resilient Grid (RECHARGE) – Annual Merit Review Presentation. [Online]: https://www.nrel.gov/docs/fy20osti/76717.pdf.

all stakeholders. First and foremost among data access stakeholders is the customers themselves. Their ownership and use of an EV is the origin point for much of the important data, and their access to information is the ingredient that helps them shape their actions beneficial to themselves and the system. Many additional entities, such as the EV manufacturer, the EVSE manufacturer, the charging service aggregator, and the power utilities, may want access to the data to influence control decisions (observability for their stable control). However, access may be restricted due to proprietary networks or mechanisms to protect the value stream of aggregators closer to the customer level (e.g., the vehicle OEM or charging service provider's data being protected from the utility).

One of the data streams to communicate will be the power levels and energy consumed by the EV, especially in the context of billing. Submetering, or installing an intermediate or independent measurement device to only monitor the EV power levels, is especially of interest to utilities with special EV rates or incentives. An industry-recognized and -accepted standard specifically for EV metering or submetering is needed to provide validity to this data stream. Charging data gives utility engineers more visibility into specific load requirements rather than having to depend on calculations based off other operating data. This is especially important during grid restoration conditions. Determining how to exchange this information for the proper observations and control for the power system will need to be addressed, leveraging developed standards, frameworks, or policies (Sections II.C.v and II.C.vi).

Closely related to the data accessibility issue is a specific use of data from EVs: the forecasting of EV-related behavior for power system planning and operations. EV capabilities are rapidly evolving, a trend that is expected to continue as more models become available and manufacturers seek ways to distinguish their product. Expanding the forecasting uncertainly, these evolutions are likely to lead to an increasingly heterogenous EV population with different behaviors; not all EVs will behave the same. Both the increase in adoption of EVs and shifts in overall behavior and capabilities may invalidate existing expansion plans, requiring a quicker response than many utilities can typically accommodate.

Opportunities

The evolving capabilities and challenges of EVs can not only be an increased burden on distribution system grid infrastructure, but also provide benefits, especially if managed as part of a larger DER framework. While cast in EV-centric terms like V1G, V2G, V2B, and smart charge management, an EV is providing (or can provide) the same services and control to the power system as other DERs (e.g., distributed storage or rooftop PV). Creating a larger DER integration framework will allow the incorporation of the unique and complementary capabilities of EVs and other DERs. This provides an opportunity to integrate these resources in a more systematic manner and leverage their full capabilities in a standard approach. Federal and private entities can help outline and define this framework to anticipate the shifting paradigm associated with consumers playing a more active role in how their devices interact with the power system.

Another significant opportunity on the distribution grid is evaluating where distribution system upgrades may be complementary to other incentives to provide the largest societal impact. Programs to incentivize replacement of older vehicles (which would have the greatest emissions impact) can be paired with targeted infrastructure improvements. Many of the lower voltage distribution systems that will have the greatest challenges integrating EVs are associated with underprivileged communities, which are more likely to own older vehicles (with greater emissions and environmental quality impacts). Studies or programs to enable these upgrades can be useful to not only providing the greatest impact, but also ensuring Americans of all economic levels benefit from the EV integration.

Takeaways

Generation capacity (amount of power produced) is not a major constraint in EV integration and could be managed while infrastructure upgrades occur (see Section II.C.iv for details). However, capacity constraints on moving the power from the generators to the loads (the transmission and distribution infrastructure) is currently a more significant limiting factor and will continue to be a complex problem to address.

Areas with lower distribution operating voltage often have the most difficult EV integration challenges. These distribution systems are often older, in less affluent areas, and represent areas where EV integration may have more pronounced greenhouse gas emission impacts.

The variations of the distribution network (voltage, size, loading, age, etc.) can lead to grid issues when integrating EVs and can have a profound impact on charging infrastructure integration strategies.

Submetering associated with integrating EVs is evolving, with existing standards being leveraged and new standards being developed, primarily for billing and revenue-grade applications associated with EV charging.

Recommendations

DOE could expand activities to work with the transportation industry and electric utilities to develop and continue refining forecasting models for customer EV charging behavior (time, location, willingness to participate in grid services) to help infrastructure planners anticipate the evolving landscape.

DOE could expand activities to work with electric utilities to help coordinate the integration of EVs into an overall optimized DER framework (high renewable DER adoption) to not only promote management of the increasing population of EVs, but also generalize them as another resource to allow utilities easier integration into their operating procedures.

DOE could expand activities to conduct research on technologies to facilitate EV charging integration in areas with limited grid capacity.

DOE could expand activities to help stakeholders to identify capacity constraints in locations where transportation electrification will likely require charging infrastructure buildout.

DOE could expand activities to work with stakeholders to help develop standards for metering requirements on EVs, especially in the context of providing appropriate information for EV for use in grid services.

ii. Strategies for integrating electric vehicles onto the distribution grid while limiting infrastructure upgrades

Basic considerations that should be included in strategies for integrating EVs onto the distribution grid include population density, vehicle travel patterns, land use, current and projected risk from natural hazards, and disadvantaged community census tracts (using the CEJST) to equitably distribute EVSE. In addition to the basic considerations there are factors that should be considered specific to limiting infrastructure upgrades.

Limiting the infrastructure upgrades to the distribution grid via VGI strategies can result in shorter development timelines for establishing charging infrastructure capabilities and lower charging infrastructure acquisition costs. Upgrading a distribution feeder is expensive and can have long lead times to implement. VGI strategies employ increased charging flexibility and distributed energy resources to enable cost effective charging in locations that might otherwise require grid upgrades to service the EV charging load.

Strategies for the integration of EVs on to the distribution grid while limiting infrastructure upgrades can be categorized into approaches that leverage the following:

1. <u>Charge time flexibility:</u> Vehicles, in many applications, spend significantly more time parked than in operation. As a result, the charging energy a vehicle may need at a given park event can be recharged in only a portion of the time the vehicle remains. Strategies can leverage this time flexibility to schedule the charging power of the vehicle(s) during periods of low grid demand to mitigate upgrades.
2. <u>Charge location flexibility:</u> Vehicles, unlike many other loads, move throughout the distribution system as they travel to new destinations during their normal operation. Charging can occur at any of these destinations given available charging infrastructure or enroute if vehicle range or existing charge is insufficient. Decisions around where to locate charging infrastructure and approaches to direct charging to occur when vehicles are in locations with higher capacity can mitigate upgrades.
3. <u>Distributed resources and site integration:</u> Deployment of distributed resources, such as photovoltaics and energy storage, can be used to reduce grid load when charging time and location are inflexible to meet travel requirements. These approaches can leverage the flexibility of other loads at a site or within the distribution system to mitigate upgrades.

The strategies above take the form of operations and planning control approaches. The operations approaches are either passive or active interventions that occur in a time horizon from a few hours to a week. The planning approaches are on a 1 to 10-year horizon and guide investment strategies by owner/operators of EV infrastructure or utilities. Table II .2 categorizes many proposed, but not all, distribution mitigation strategies by their time horizon and approach.

Table II.3. Distribution mitigation strategies.

Strategy	Charge-Time Flexible	Charge-Location Flexible	DER and Site Integration
Operations (time horizon is hours to a week)			
Smart Charge Management			
Time-of-use (TOU)	X		
Real-time price	X		
Randomized charging	X		
Behind-the-meter			X
Feeder peak avoidance	X		
Directed charging		X	
Smart Inverter			
Volt/VAR	X		
Bi-directional (V2G)			X
Planning (One to ten years)			
EV Hosting Capacity			
En route charging		X	
Destination charging		X	

Smart Charge Management: The operations strategies described below minimize grid impact by shifting charging energy through leveraging charge-time, charge-location, and/or the flexibility of other distributed resources. The Smart Charge Management strategies outlined in the section fall under the Energy Scheduling Service or Reserve Service outlined in the earlier Grid Services discussion in Section II.B and the techniques to implement these strategies are included in Section II.C.vii.

Time-of-use (TOU): In the TOU control strategy, a driver (possibly through an automated system in the EV or EVSE) chooses to let a vehicle respond to energy price incentives by charging a vehicle within a beneficial time window to reach the required state of charge. This charge control is a decentralized and passive strategy in that the identified window(s) are specified in published rate tables based on time of day and/or season that are infrequently changed based on historical trends after they are approved by the relevant utility regulator. Implementation of the control can vary and may occur immediately at the beginning, randomly within, or at the end of the TOU window.

Real-time Price (RTP): An automated system in the EV or EVSE responds to energy prices, which change on a regular basis to minimize the total cost of charging while meeting the required state of charge before departure. This control is a centralized and active strategy in that it requires a price to be set by the grid operator based on the current grid state and continuous feedback on the new price is provided to all EVs or EVSE within an area.

Randomized Charging: A stochastic strategy to randomly distribute EV charging within a vehicle dwell period. This control is decentralized and passive in that it only relies on the vehicle travel pattern to determine the dwell window and the averaging effect of the long dwell period of many vehicles.

Behind-the-meter: A decentralized control strategy across the distribution grid that coordinates the charging of EVs within dwell based on site constraints. This active control is typically relying on centralized control for the site and can have multiple objectives to (a) minimize demand charges, (b) defer capacity expansion to support charging, and (c) to coordinate with distributed energy resources and other flexible loads to minimize energy costs for the site.

Feeder peak avoidance: A centralized control strategy that shifts EV charging within vehicle dwell to minimize feeder peak. This active control can be implemented through an aggregator communicating to a utility DERMS to identify when a feeder peak will occur and directly control the charging of the vehicles while meeting their travel and energy requirements.

Directed Charging: A centralized control strategy for en route charging in which a vehicle driver is provided with an incentive to choose to charge at a fast-charging station along their route or with a minimal detour that minimizes peak load at a charging station.

Smart Inverter: These operations strategies minimize grid impact through advanced inverter functionality to charge and discharge energy storage within the vehicle. The smart inverter strategies outlined in the section fall under the Regulation Services or Voltage Service outlined in the earlier Grid Services discussion in Section I.B.

Volt/VAR: A decentralized strategy that uses the EV charger or DC charger (inverter) to provide reactive power as a function of the measured voltage as an active response to changes in the grid. This strategy supports the voltage through either a passive approach in which the voltage curve, which triggers the reactive response, can be programmed into the EV or EVSE is fixed or active in which the curve can be updated frequently in response to changes in the grid. This approach relies on charge-time flexibility as the use of reactive power reduces the real power that can be used to charge a vehicle, thus slowing down the rate of charging.

Bi-directional (V2G): A strategy that uses the EV charger or DC charger (inverter) to provide real and reactive power from the vehicle to support the grid. This approach leverages charging time flexibility where the energy in the vehicle is sufficient to discharge the vehicle to support the grid and either recharged prior to departure or is sufficient to meet future travel needs before the next opportunity to charge. The implications on battery life are included in Section II.B.i and the technology needed for this approach is included in more detail in Section II.C.vi.

EV Hosting Capacity: These planning strategies minimize grid impact through identification of grid infrastructure with existing capacity for installation of new chargers that help shift charging load to ideal locations for EVs and the grid. These approaches inform future grid infrastructure buildout to include EV load growth in conjunction with other recurring maintenance and grid improvements.

- En route Charging: A strategy that identifies locations for installation of fast charging, whether along travel corridors or within metro areas that also have existing grid capacity for high-power charging systems. These locations are where EVs may need to be quickly recharged along their route before continuing to their next destination. Typically, this charging need is for long distance travel at or beyond the range of the EV in which the length of the trip presents charge location flexibility.
- Destination Charging: A strategy that identifies locations for charging where EVs are parked for longer dwell times and where there is existing grid capacity to host AC and DC charging.

Takeaways

- There are multiple strategies that can be used to minimize grid infrastructure upgrades necessary for EV charging. Each strategy offers different applicability, costs of implementation, and value.
- There are planning strategies for the intelligent location of charging infrastructure and operational strategies to control charging that minimize grid upgrades. These strategies leverage the charging time and location flexibility of EVs. These strategies should also consider population density, vehicle travel patterns, land use, current and projected risk from natural hazards, and disadvantaged community census tracts (using the CEJST) to equitably distribute EVSE.

Recommendations

DOE could expand activities to conduct further analyses and demonstration of these strategies to determine value and effectiveness when deployed in common use cases as well as less common evacuation and emergency preparedness use cases.

iii. The changes in electricity demand over a 24-hour cycle due to electric vehicle charging behavior

As electric vehicle adoption expands, the level of charging demand across the country will rise. The nature of this load growth will be a factor of many things, including vehicle efficiency, charging power, miles traveled, and vehicle dwell periods. These factors will define charge session durations and the periods when those charge sessions could occur. However, those dwell periods must occur near EVSE in order for a charge session to occur. Therefore, the deployment of infrastructure will also have an impact. Figure II.5 depicts a 24-hour load profile during a peak load day for the cumulative load in the Atlanta metro area, including both the base load – without EVs – and with the addition of EV charging loads – accounting for approximately 13% of the light-duty stock of personal-use vehicles[98]. The same Atlanta metro area base and EV loads are represented in Figure II.6, but in this case occur on a day with the minimum peak base load. These two figures are based on actual load in the Atlanta metro area and do not represent the variation in load over a 24-hour cycle for all regions/utilities across the United States.

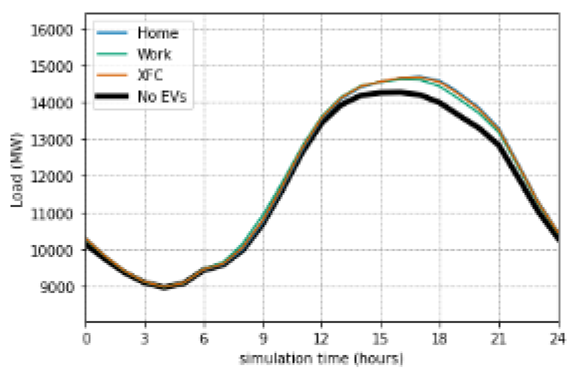

Figure II.30. (Left) Peak Load + Uncontrolled EV Charging.

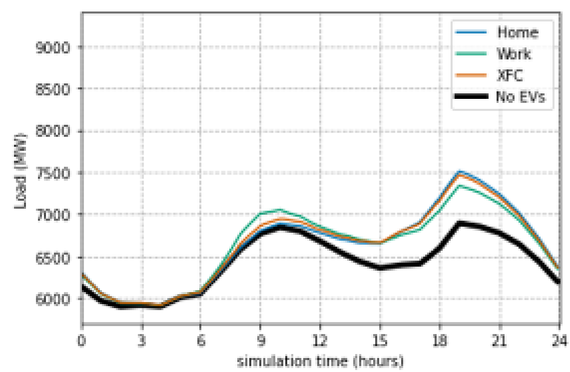

Figure II.31. (Right) Minimum Load + Uncontrolled EVs.

The three different EV scenarios considered in

Figure II.5 and Figure II.6 represent different EVSE deployment strategies where consumers are assumed to prefer charging at "Home", "Work", or public en route Extreme Fast Charging "XFC" stations. The "Home" and "Work" scenario assumes that EVs at all residential locations have onsite access to EVSE. The "Work" scenario assumes additional EVSE access at workplaces. The XFC station preference illustrates a case where EV adoption in multi-family residential locations have limited access to EVSE and therefore charging occurs similar to refueling of conventional vehicles at a gas station. On a city-wide scale, the most significant impact is both for the peak day and minimum load day, the base load peak occurs in the late afternoon, which is coincident with the largest concentration of EV charging. The coincidence peak between the base load and EV charging will increase peak load on distribution equipment and require the use of more expensive generation (e.g., peaker plants) and/or conventional power sources (e.g., coal or natural gas). The impact of uncontrolled charging is more clearly seen on the minimum load day where in the Work scenario the increased use of workplace charging shifts EV loads earlier in the day. This shift in load leverages charging location flexibility of the EVs and results in a relatively lower peak demand. The afternoon peak reduction is limited in this scenario by the travel profiles of the vehicles and a requirement to fully charge the vehicles on a daily basis. With different constraints, it might be possible to shift more energy out of the afternoon peak

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[98] Bennett, J. et al. 2021. "Charging Infrastructure Technologies: Smart Electric Vehicle Charging for a Reliable and Resilient Grid (RECHARGE)." Presented at the *U.S. Department of Energy Vehicle Technologies Office Annual Merit Review*, June 23, 2021.

with workplace charging, though this could simply move the peak into the midday. All three scenarios increase demand over the based load when charging is uncontrolled. This section will explore the many approaches to mitigate the increased load from EVs or further decrease the base load over a 24-hour cycle through the operations and planning strategies discussed in Section II.C.ii.

Typically, electrical loads must occur when demand for energy is required, such as when it is dark for lighting or when it is hot for air conditioning. However, the dwell periods for EVs often far exceed the time required to fully recharge the vehicle's battery. Therefore, in addition to being one of the most powerful devices in a residential home or in some commercial buildings when aggregated, EV charging will also be one of the most temporally flexible. To understand this flexibility, it is important to consider the possible shift that would occur from an increased focus on home or workplace charging.

The load profile in Figure II.7 is from a single distribution feeder which contains commercial and residential load. This figure depicts the base load, as well as EV charging load for home and workplace charging scenarios, prior to the implementation of SCM controls. These uncontrolled loads represent how a focus on workplace charging can shift loads to earlier periods in the day, when many vehicles are dwelling at work locations. It should also be noted that, unlike the city-wide analysis from

Figure II.5 and Figure II.6 in which all feeders are represented, the energy consumed by EV charging is not consistent between the home and work scenarios due to vehicles moving between different feeders throughout the day. This movement of energy requirements throughout the city can also represent a method for load flexibility to move energy from one feeder to another.

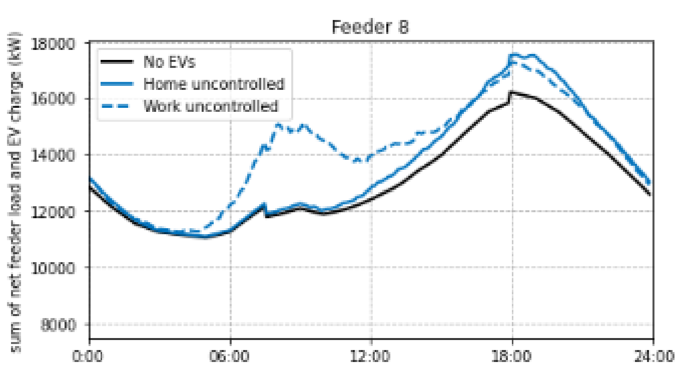


Figure II.32. Peak Load + Uncontrolled EVs – Residential and Commercial Atlanta Feeder.

While the comparison of different EVSE deployment strategies above displays how EV loads can shift based on charging preferences, the charging loads are operating in an uncontrolled manner where each charge session begins at the start of a vehicle's dwell period. This approach does not take advantage of the long dwell periods of most vehicles, presenting an opportunity for a more sophisticated approach. Charge management strategies, which rely on incentives (see Section II.C.v and II.C.vi) to motivate participation by owners can have a more significant and targeted effect. These strategies leverage the flexibility of the EV by incentivizing charging in periods that are beneficial to the grid and to the EV owner.

Advanced SCM controls can influence EV charging to achieve high levels of load shaping across an entire metro area. Figure II.8 displays the cumulative base load for 11 feeders in the Minneapolis metro area with controlled scenarios for multiple strategies under the home charging preference. These feeders were selected for analysis as they provide a mix of residential, commercial, and industrial load. The residential feeders selected are in an area expected to have higher early adoption that exceeds the city-wide adoption of 13% and the EV load accounts for approximately 53% of the light duty vehicles[99]. This case is analyzed with 13% adoption across the Minneapolis metropolitan area—similar to the Atlanta analysis— with the difference in adoption in these selected feeders a result of travel to and charging in these locations as well as an increased adoption rate in the selected regions.

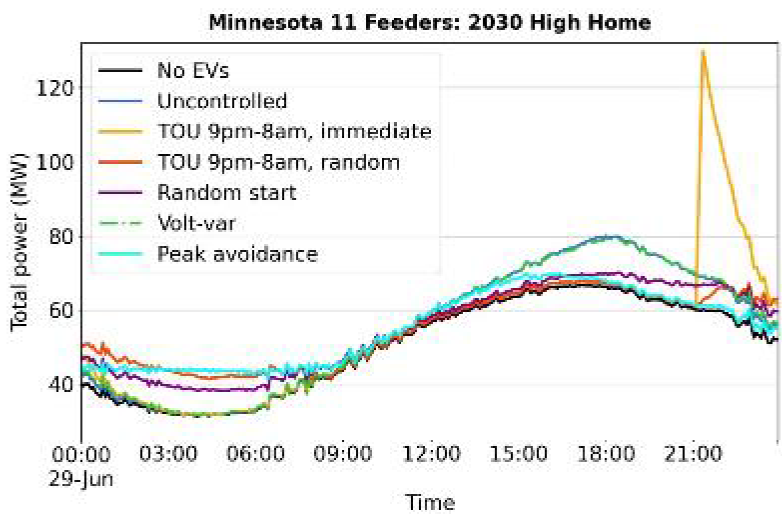


Figure II.33. Peak Load + Controlled EV Load for 11 feeders in Minneapolis.

The uncontrolled scenario (see blue line in Figure II.8.) for this region represents drivers with a preference for home charging where each charge session begins at the start of a dwell period. The timing of this load coincides with the existing base load peak, which could require the upgrade of distribution equipment or the need for more expensive generation, unless alternative strategies are explored.

The “TOU immediate” charging profile (see yellow line in Figure II.8.) represents the same energy demand and preference for home charging, but all charge sessions wait to begin until the off-peak pricing for the region starts at 9:00 PM. These TOU rates are designed to create an incentive to shift loads to more desirable periods of the day, typically when generation costs

[99] 11,187 EVs across 10 feeders assuming an average 1.8 vehicles per household.
Bennett, J. et al. 2021. “Charging Infrastructure Technologies: Smart Electric Vehicle Charging for a Reliable and Resilient Grid (RECHARGE).” Presented at the *U.S. Department of Energy Vehicle Technologies Office Annual Merit Review*, June 23, 2021.

are lowest, or equipment capacity is highest. However, this charging behavior creates a rebound or timer peak a few hours after the uncontrolled charging would have occurred during the base peak load. Although this demand spike is later in the day than the base peak load, it is so significant that a much larger peak is observed with nearly double the magnitude of the uncontrolled scenario. In some cases, demand spikes later in the day, such as off-peak hours, may result in utilization of conventional power sources (e.g., coal or natural gas) because solar power will no longer be generated at the time of use. This scenario shows that the method in which EVs respond to TOU rates can have adverse effects at higher adoption levels, thus demonstrating the need for holistic SCM approaches that account for the broader impact of all EVs.

While the immediate TOU is an extreme case represents a possible, but unlikely, scenario with complete TOU EV charging compliance, it also displays how powerful incentives can be for influencing EV charging behavior. The increasing adoption of EVs should not be considered a liability to the grid, but rather an asset. The chart in Figure II.9 contains the same charging loads as in Figure II.8, but the TOU immediate control and base loads have been removed for clarity. In this figure it is clear the TOU random control (see red line in Figure II.9), in which the start time of the charge session is randomized within the TOU window, mitigates the rebound or timer peak while still shifting EV load within the TOU window. This will meet the needs of TOU rates and mitigate the effects on peak demand, resulting in the need for fewer upgrades and avoiding the use of more expensive generation.

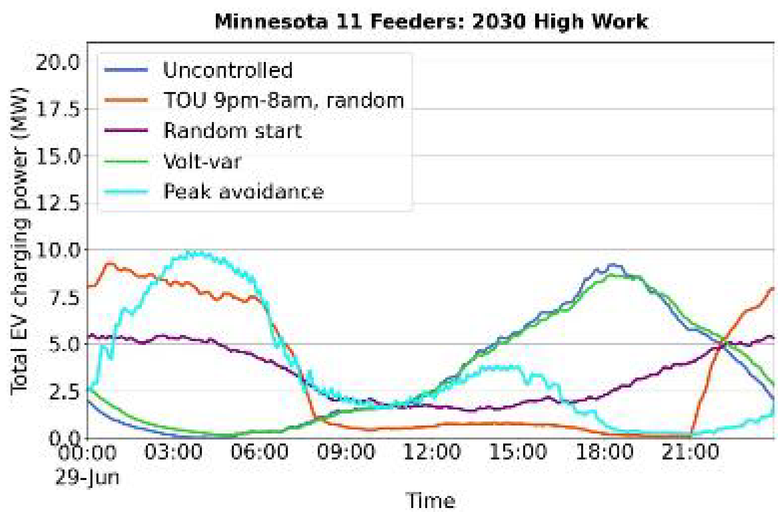


Figure II.34. Uncontrolled and Controlled EV Load for 11 feeders in Minneapolis.

The simpler randomized charging, or random start (see magenta line in Figure II.9), control results in a more consistent EV load that is distributed throughout the day, mitigating the feeder peak, but is not targeted toward any specific goals, such as maximizing renewables. This is in contrast with the more sophisticated control which shifts EV charging to periods when the base load is the lowest, avoiding the impact on feeder peak demand and increasing consistency in grid load. These controls represent how flexible EV charging can be and how, with the right incentives and control, loads can achieve goals such as peak reductions or even to consume energy when lower cost generation sources are producing the most power. Though such control strategies may have secondary issues of their own (e.g., changing transformer cooling cycles that lead to shorter equipment life), they still demonstrate the flexibility of the EV charging load and the ability to leverage charge time and charge location flexibility to help mitigate various impacts to the grid. However, more research is needed to determine which strategies in a particular region will maximize value by achieving goals such as the utilization of renewables as the generation source for EV load.

The demand presented in this section has focused on normal daily travel. V2X introduces new opportunities that may alter customer behavior and will vary depending on the type of customer and their primary motivations. V2X could be used to shift load and discharge back to the grid to help meet demand during peak periods. More analysis is needed to understand the impacts of V2X on the normal 24-hour load. Additional analysis also needed to prepare for customer charging behavior in the days or moments before a known grid disruption. During emergencies, such as the wildfires in California and the 2021 Texas power crisis, customers with EVs will want to ensure travel during these events and further those with bi-directional EVs may want to charge and use their vehicles for backup generation.

Takeaways

- The charging behavior of uncontrolled EVs can change the 24-hour electricity demand increasing peak load or potentially shifting when a peak may occur. These changes in demand will differ at the feeder-level and across a wide-scale metropolitan area.
- Charge management strategies to influence EV charging behavior can be very effective in changing the 24-hour demand profile and strategies should consider the approach holistically to prevent unintended secondary effects.
- Charge management strategies to shift charging behavior are dependent on both charge location and charge time flexibility, noting that each are respectively reliant on charging infrastructure deployment and vehicle travel constraints.

Recommendations

- DOE could expand activities to evaluate the effectiveness of charge management strategies to identify which strategies provide the most value to the grid, especially for future EVs@Scale adoption.
- DOE could analyze how EVs can enable greater integration of clean DER to benefit the grid by shifting demand.
- DOE could expand activities to further study the potential for V2X capable vehicles to benefit the grid through shifting load in the 24-hour demand by leveraging their storage capability.

iv. Load Increases Expected from Electrifying Vehicles

EVs@Scale necessitates the assessment of and possible modification to the U.S. electric power generation, transmission, and distribution system. Large-scale adoption of EVs affects the U.S. electrical grid in two principal aspects. This includes the point of common coupling, which for most EV charging stations is a connection to the distribution system, either at home, workplace, or public charging station and the bulk power system as an aggregated new load. The following section presents two studies on the impacts of EVs@Scale (including light-, medium-, and heavy-duty EVs) on the bulk power system; briefly discusses transmission, distribution, and other challenges; and provides key takeaways and recommendations.

EV Load Increases and U.S. Grid Energy Generation and Capacity

The Grid Integration Tech Team (GITT) and Integrated Systems Analysis Tech Team (ISATT) of the U.S. DRIVE Partnership examined a range of light-duty EV market penetration scenarios (low, medium, and high) and associated changes to the U.S. electric power system in terms of energy generation and generation capacity. The objective of this study was to gauge the sufficiency of both energy generation and generation capacity in the U.S. electric power system to accommodate the growing fleet of light-duty EVs. Energy Generation is the total amount of electrical energy, commonly expressed in megawatt-hours (MWh), produced at the generating stations and Generation Capacity is the maximum output, commonly expressed in megawatts (MW), that generating equipment can supply to system load, adjusted for ambient conditions. The future potential changes in energy generation and generation capacity as a result of growing light-duty EVs, in turn, were compared to historical trends. This includes explicit quantifications for the year 2030 as it roughly corresponds to the period of highest annual EV market growth in the high EV market penetration scenario that was considered.

This study utilized U.S. light-duty market projections by EPRI including a series of three market scenarios building off actual EV sales through 2016. The EV market growth in the three scenarios (low, medium, and high) are depicted in Figure II.10. As shown in the figure, EV sales in 2030 are estimated to total 320,000 (2% of new vehicle sales), 2.2 million (12%), and 6.8 million (40%) in the low, medium, and high scenarios respectively. These scenarios result in a total EV fleet size (i.e., cumulative vehicles sales) of 3 million (1% of the total passenger vehicle fleet), 14 million (5%), and 40 million (15%) vehicles by 2030, respectively.

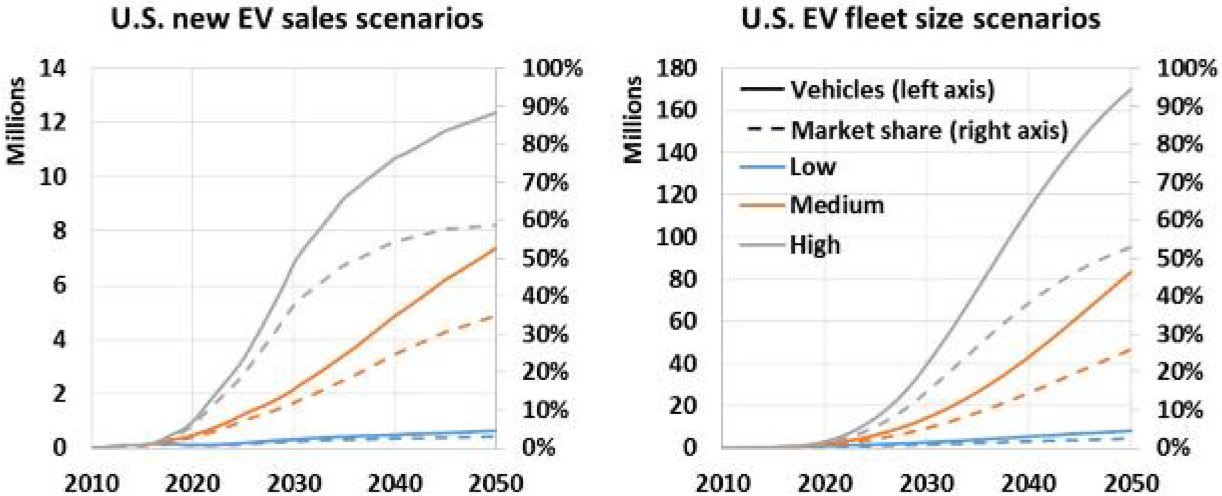


Figure II.35. EPRI low, medium, and high PEV market penetration scenarios, shown both as annual sales (at left) and total PEV fleet size (i.e., cumulative vehicles in service, at right). Solid lines correspond to number of vehicles (left axes) and dotted lines correspond to sales shares (right axes).

The U.S. electric power system has evolved over time to accommodate new energy demand (see Figure II.11). In the 20-year period from 1999-2018, the annual growth in energy generation (i.e., total electricity consumption, or load and system losses) has averaged 30 TWh. While the last decade has seen less than 5 TWh added each year, historically, there have been periods when the grid added nearly 100 TWh every 5 years. Periods of highest energy generation growth included expansions to baseload generation from nuclear and fossil sources at a time when the policy environment allowed for necessary investment.

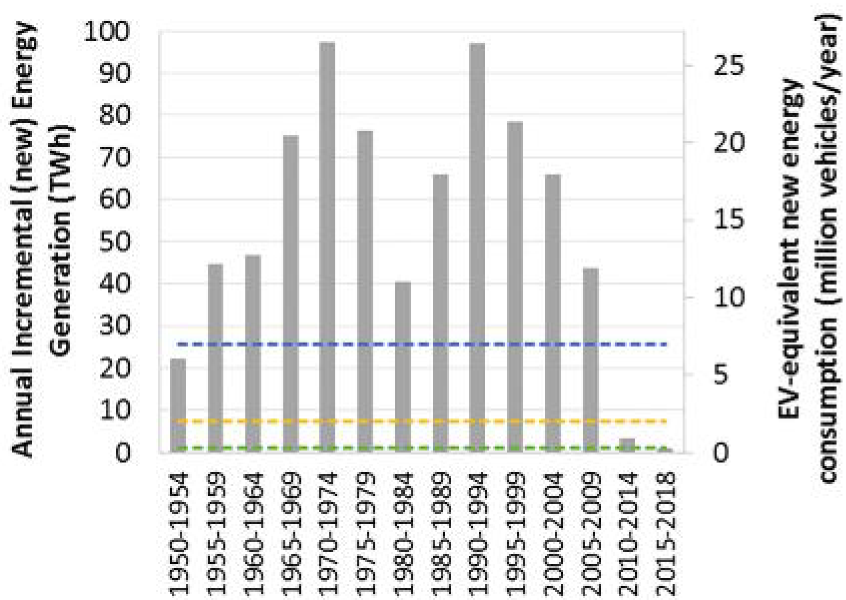


Figure II.36. Historical data showing U.S. annual incremental (new) energy generation over time, averaged in 5-year increments. Energy generation associated with EV sales shown for the 2030 low, medium, and high scenarios considered at 1, 8, and 26 TWh, respectively, for context.

For the 2030 low, medium, and high EV sales projection scenarios, this translates into 1, 8, and 26 TWh of incremental energy generation, respectively. These increases in energy generation are relatively small compared to the 100 TWh range shown in Figure II.11. These historical comparisons illustrate that there have been sustained periods of time in the past where growth in generation to serve new load exceeded the ranges of additional electricity consumption and peak demand associated with the future EV market scenarios.

Pacific Northwest National Laboratory (PNNL) has conducted a study focusing on the bulk power electricity impacts from EVs@Scale. This study focuses on the western grid (i.e., the Western Electricity Coordinating Council (WECC)) as the WECC already has commonly agreed-upon data set for a future grid scenario – the WECC 2028. By using the WECC 2028 scenario, PNNL used the best available future grid scenario definition that included load growth assumptions, generation retirements and additions, as well as transmission expansion. This study is unique because it represented for the first time not only the market projections for light-duty EVs, but also market projections for medium-duty and heavy-duty EVs. This study focused on resource adequacy for high EV adoption as the WECC grid planners defined the evolution of the bulk power system to the year 2028. This analysis applied the following penetration assumptions for 2028 expressed as a national figure: light-duty EVs: 24 million, medium-duty EVs: 200,000, and heavy-duty EVs: 150,000. The national figures were applied to the WECC footprint through a 0.4 scaling factor. Load profiles were generated for light-duty EVs by NREL using the EVI-Pro tool and medium- and heavy-duty EV load profiles were generated through modelling by PNNL. The cumulative WECC base load and added EV load is presented in Figure II.12 for the case of “Home High Power No Delay Charging” where most EVs start charging upon arrival at home in the evening.

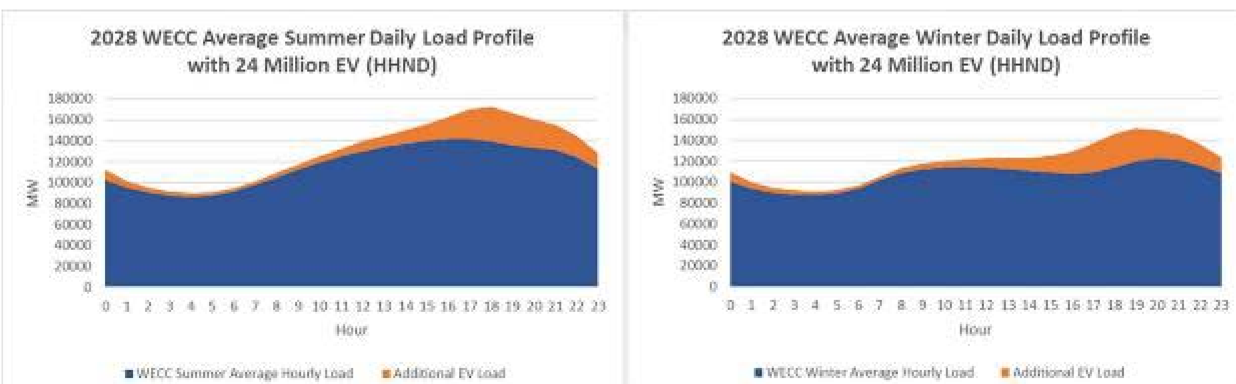


Figure II.37. Illustration of WECC base load and added EV load for “Home High power No Delay charging.” EV load consists of 9 million LDVs, 70,000 MDVs, and 94 HDV charging stations. (The left frame represents summer load, the right frame winter load.)

The major finding of this study is that resource adequacy is likely to be sufficient for high EV penetration scenarios. Under a high-penetration scenario with electric fleet sizes for the WECC of 9 million LDVs, 70,000 MDVs, and 94 HDV charging stations, generation and transmission issues are not expected under normal operating conditions (normal system, weather, and water conditions). However, under non-normal conditions, that may include low hydro conditions, extreme weather conditions, transmission line outages due to wildfires and unplanned power plant outages occurring concurrently, maintaining reliable operations may be challenging even at lower EV penetration levels. Alternatively, if managed charging was applied by hypothesizing a price-minimization scheme, the EV resource adequacy could be expanded to 65 million (national fleet number) or 19.6 million for the WECC. This suggests a significant opportunity to substitute additional generation and transmission requirements with smart charging strategies and achieve much better utilization of the existing grid. Figure II.13 illustrates the resource adequacy for unmanaged and managed charging where the resource adequacy limit is met when the unserved energy becomes greater than zero. At the maximum number of LDVs, transmission congestion was found to be the limiting factor. This means that there are some available power plants in the WECC, but the electric power could not be delivered to the load centers because of transmission limitations.

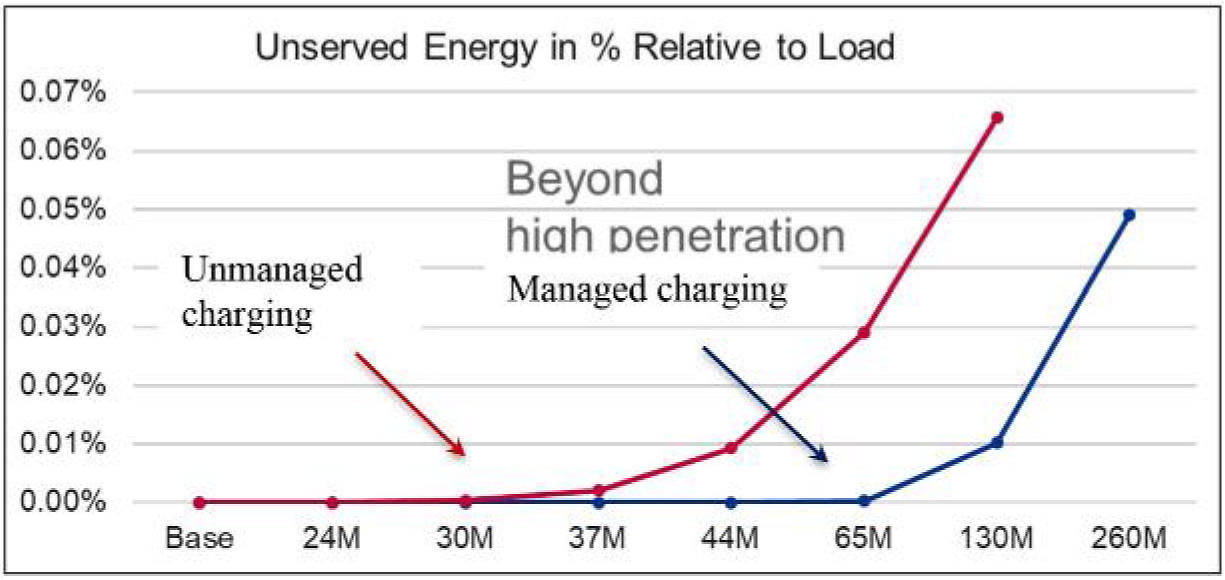


Figure II.38. Limits of resource adequacy for unmanaged charging (red) and managed charging (blue) based on unserved energy under increasing LDV penetration scenarios. Note that the LDV penetration numbers on the x-axis are the national penetration numbers. Penetration numbers for MDVs and HDVs were kept constant at 200,000 and 150,000, respectively. The WECC numbers must be scaled back by a factor of 0.3 because the WECC is projected to operate 30% of the national LDV EV fleet.

Transmission, Distribution, and Other Challenges

Despite the positive outlook with regards to the electric grid's ability to meet energy generation and capacity requirements for high levels of EV penetration, challenges do exist at the distribution and transmission levels. Within Phase I of the PNNL study, an illustrative distribution system analysis was prepared that projected expected results and outcomes. It indicated that the factors most likely to limit additional growth of EVs are thermal overloading and reaching the rated capacity of grid assets in the distribution system under fast charging conditions. Voltage violations may occur under fast charging conditions that feature high ramping loads during fast charging events. Phase 2 of the PNNL study on EVs@Scale focused on distribution system analyses, outlining approaches to improve the EV adoption placement using additional socio-economic metrics and examining the impacts and cost to the system as EV adoption progresses. The Phase 2 analyses evaluated how infrastructure upgrades or smart charge management could be used to mitigate the voltage and thermal violations, with smart charge management able to mitigate the issues on the system studied. At this time, further assessment of the grid under high EV penetration scenarios is needed in the following areas:

High-power charging of light-duty EVs (at 150 kW and above), high-power charging of medium- and heavy-duty vehicles (potentially at over 1 MW), legacy infrastructure constraints in dense urban areas, and low-power charging of light-duty EVs on residential circuits.

Transmission constraints must be deliberately assessed as investments in the U.S. power system are expensive and time consuming.

Ramping capabilities of the generating fleet and spinning reserve requirements of the bulk power system should be considered for EVs@Scale.

Medium- and heavy-duty vehicles account for 29% of the U.S. on-road transportation fuel use and further analysis of medium- and heavy-duty EV market growth scenarios are needed to assess the impact on energy generation and energy capacity.

There are also additional issues to consider with regards to the ability of the U.S. electric grid to meet the energy requirements of EVs@Scale. As discussed in Section I.D of this report, electrification for EVs@Scale requires transportation and energy sector "coupling" analysis to ensure that reliability and resilience are maintained, or significantly improve, as society becomes more reliant on the grid. Here, the magnitude and distribution of EV loads can be assessed and articulated, but their aggregated impacts on different locations of the transmission and distribution systems should be considered together. Furthermore, expansion of the electric grid come with significant cost implications. While the aforementioned PNNL study provided insights into production cost and locational marginal prices on an hourly basis, this approach did not consider the evolution of the grid infrastructure as new investments are made. It would be beneficial to consider new cost and revenue analyses as part of future assessments.

Takeaways

- It is expected that energy generation and capacity requirements can be managed with proper planning for EV penetration and resulting charging demand to support a growing EV fleet. Although the issues vary geographically and are use-case specific, they do not undermine the overall conclusion that at the generation level EVs@Scale will not prove a significantly greater challenge than past evolutions of the U.S. electric power system.
- Transmission and distribution, however, may prove to have significantly greater challenges and need considerably more assessment to identify constraining aspects and will require innovative and proactive solutions and strategies.

Recommendations

DOE could expand activities to work with all stakeholders (which includes community and environmental justice representation) to develop tools for assessing the impacts of high-power charging of light-, medium-, and heavy-duty vehicles on utility distribution and transmission systems.

- DOE could expand activities to assess the ability of innovative strategies to minimize the impacts of the adoption of EV infrastructure on distribution grids in dense urban, rural, capacity constrained areas, including disadvantaged communities, and tribal lands.
- DOE could expand activities to conduct further analyses of medium- and heavy-duty EV market growth scenarios and impacts on energy generation and energy capacity.
- DOE could expand activities to assess the implications to the grid of new high-power charging technologies as they are developed by industry.
- DOE could support utilities in their planning of, and manufacturers supporting the supply of transformers and grid components to expand the capacity of the transmission and distribution grid.

v. Potential for Customer Incentives to Shift Loads

Electric vehicles have unique attributes from a grid perspective – they do not consume energy from the grid when in use and, and in some instances, such as privately owned passenger vehicles, the vehicle may sit idle for a large number of hours. This makes them unique from other utility loads in that they may be able to shift load to a *time or location* when the grid has available capacity or an overabundance of renewable energy without impacting transportation needs, offering distinct opportunities to shift load and to provide other grid benefits[100] [101]. While the collective opportunity is large, incentives are needed to motivate and compensate consumers (e.g., individuals and fleets) and businesses (e.g., third-party aggregators and EV manufacturers, EVSE OEMs, etc.) to participate.

An incentive is a signal from one actor in the system to another, where value is offered with the intent of modifying a decision or behavior. EVs have unique qualities that merit consideration of how incentives can aid in achieving EVs@Scale. Incentives can have accuracy, precision and other attributes, which speak to the extent that they are capable of shifting load or providing any other grid service with respect to time, location, or magnitude. Broadly speaking, incentives are an economic payment that compensates customers for changing their behavior. Well-designed incentives result in net benefits to all parties (i.e., benefits to customers and grid operators) and can associate value with a variety of beneficial grid services, such as load shifting, demand reductions, avoided upgrades, backup power, or increased renewable energy in lieu of conventional fossil fuels. For instance, EVs and other DERs, such as PV or flexible assets, could be subject to an electric rate designed to manage peak capacity on a distribution line, but associated complexity and cost considerations must be understood[102]. It should be noted that incentives are not one-size-fits-all, and light-duty, medium-duty, and heavy-duty vehicles have distinct usage patterns that must be understood and respected. Commercial vehicles (MDVs and HDVs) do not have as many idle hours as personal vehicles, but they also present opportunities because they can have predictable usage patterns. The amount of

[100] Kempton and Letendre, 1997. Electric vehicles as a new power source for electric utilities in *Transportation Research Part D: Transport and Environment*, vol. 2, no. 3, pp. 157–175.
[101] Bates and Leibling, 2012. Spaced out in *Perspectives on parking policy*, vol. 9.
[102] Jha, Singh, Kumar, Dheer, Singh, Misra, 2020. Day ahead scheduling of PHEVs and D-BESSs in the presence of DGs in the distribution system in *IET Electrical Systems in Transportation*, vol. 10, no. 2, pp. 170–184. [Online] https://ietresearch.onlinelibrary.wiley.com/doi/pdf/10.1049/iet-est.2018.5096.

flexibility and the degree to which load can be shifted are highly dependent on the vehicle's use case. Commercial medium- and heavy-duty vehicles will have larger batteries that offer more capacity which could provide a larger singular value, and therefore special incentivization.

Incentives span a spectrum of approaches that range in complexity and the amount of control afforded to grid operators who have to respond to grid conditions. Incentives can influence the time, place, or amount of a grid service provided. The cost to implement these incentives differs depending on the approach, and many hurdles must be overcome to drive consumer behavior. Any incentive requires design and forethought and should be subject to a cost-benefit analysis process such as those outlined in the National Standard Practice Manual[103] or similar rigorous process. Hurdles include opportunity costs, such as battery degradation, that would have to be offset in order for the vehicle owners to be willing to provide certain system benefits. At low EV adoption levels, less sophisticated approaches, such as rebates or one-time bill credits, will likely be sufficient for mitigating negative impacts and raising awareness among consumers. However, as the number of electric vehicles increase and become a more substantial portion of a utility's load, more complex approaches, such as real-time pricing or grid services markets, will likely be necessary – particularly at the distribution level where energy markets do not currently exist. More sophisticated measures will offer more or better control but should be seen as adding value on top of simpler incentives, and not usually replacing them. Mitigating negative impacts to the grid, shaping consumption to align with decarbonized generation, and minimizing utility investments in response to growing numbers of electric vehicles will require a portfolio of incentives.

[103] National Standard Practice Manual for Benefit-Cost Analysis of Distributed Energy Resources. https://www.nationalenergyscreeningproject.org/national-standard-practice-manual/

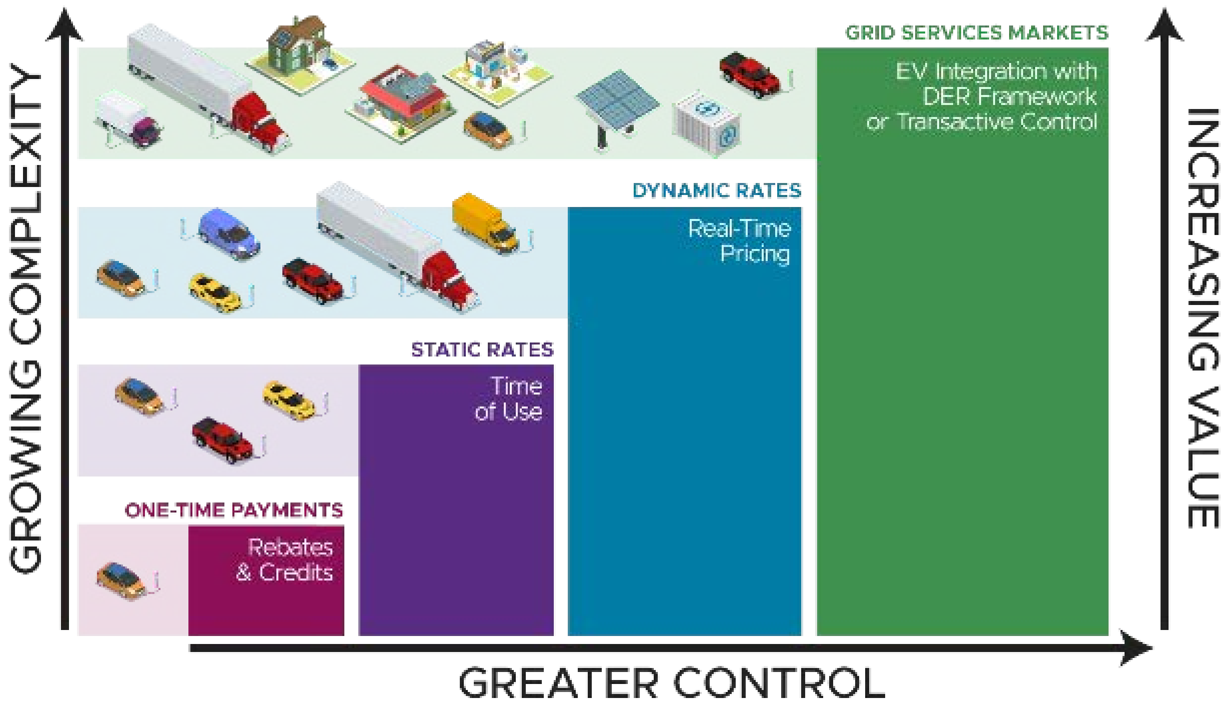


Figure II.39. Customer incentive strategies.

Incentive strategies can be categorized into four broad categories as shown in Figure II.14: one-time payments, static rates, dynamic rates, and grid services markets. Rates occupy two categories to acknowledge that there are substantial differences in terms of complexity to implement, potential for benefit, and associated costs (potentially) on both the grid and customers. At one end are one-time payments that are simple tools that provide generalized benefits and are the easiest and least costly to implement. Rates are a more refined tool that can adjust pricing from not at all (flat rates) to those based on grid conditions for specific times and/or locations, designed to save consumers money while incentivizing behavior dynamically. At the far end is the development of grid services markets that compensate customers and other market participants not only for electric vehicle participation but also accounts for participation of other energy resources (e.g., PV, stationary battery storage) to respond to system constraints. This includes bi-directional electric vehicle capabilities such as vehicle to load (e.g., home or building) or vehicle to grid, collectively referred to as V2X. The integration and prioritization of renewables can also become more sophisticated, so they are optimized and maximized. Grid Services Markets differ from rates in that prices are not determined by a formula with variables but rather through competition among grid service buyers and sellers. As the incentive mechanisms become more sophisticated and their accessibility to the grid or other actors increases, each has accompanying increases in cost, complexity, and potential value. In addition, the benefits that additional control provides become more refined so that temporal and spatial aspects can better target customer behavior to system or grid constraints or opportunities. Additional controls could also be paired with more capabilities, such as two-way flow networks (e.g., vehicle to grid) to provide more capacity within specified concentrations, or to prioritize charging when renewables are generating power.

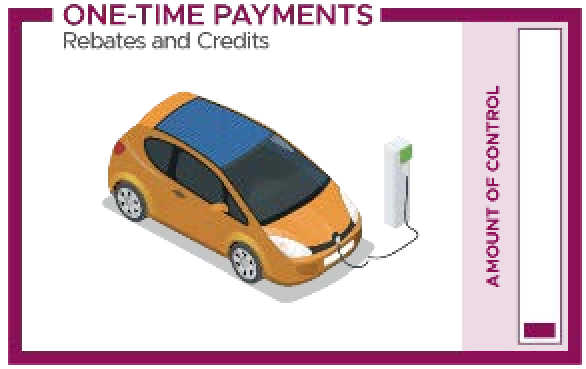
No single strategy will work for all use cases of vehicle grid integration. Charging power level and dwell times differ but so will the needs of the grid. For example, low-power, long-duration charging, such as when an EV is parked overnight, has more temporal charging flexibility than short-duration, high-power charging, such as at a public DC fast charging station. Utilities will need to employ a variety of strategies, and the benefit achieved by each strategy will have to be greater than the cost to implement it. Importantly, strategies will have to have a sufficient value proposition for customers while remaining convenient and easy to understand, so that participation does not interfere with the primary purpose of the vehicle – transportation.

The nascent nature of the electric vehicle market means that the size of market and the willingness of customers to participate is yet undetermined. Utilities are at the initial stages of developing charge management programs as well as vehicle to grid programs and trying to understand customer preferences and motivations. Early research has provided insights but is based on early-adopters who will not necessarily be representative of the broader population. For example, wealthier EV owners who own multiple vehicles may be less price sensitive compared to the general population. They may also be willing to prioritize charging during peak renewable energy generation to ensure carbon-free generation is not curtailed. Price and source of power could both become drivers. As electric vehicles become more mainstream, and the customer base becomes more diverse, further research will be needed to obtain a more representative assessment of the motivations of drivers and the limits of their willingness to participate in charge management and vehicle to grid programs.

Current State

Utilities across the country are designing – and state commissions are approving – a range of strategies that can influence customer charging and discharging behavior utilizing the unique attributes of electric vehicles to mitigate negative impacts as well as provide other benefits to the grid. Charging power differences, customer use cases, and utility operational differences will govern the applicability of any type of incentive. Any approach must consider the complexity and costs of implementation relative to the benefits provided to different actors. For instance, the benefit to customers must exceed the cost to a customer's convenience, just as the benefit to program providers must outweigh the implementation costs. Costs can include hardware costs as well as the specific amount of the incentive, and program administration costs. The electric vehicle market in California is further evolved due to the large number of electric vehicles throughout the state, and utilities there have been performing robust analysis and piloting various incentive programs.

One-Time Payments

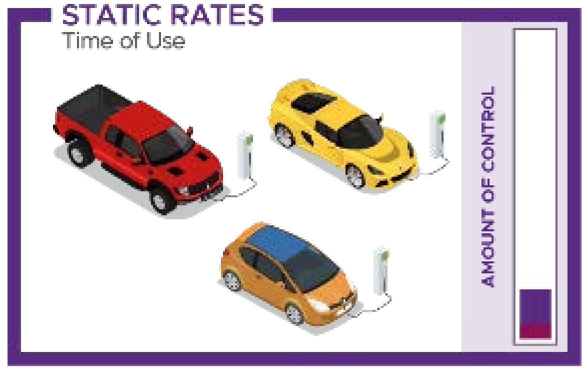


The simplest or most basic incentives for shifting load are rebate or credit programs. These incentives pay the customer in exchange for specific actions that occur once or infrequently. Electric vehicle and/or charger rebates are simple approaches that have indirect benefits that can be highly valuable to utilities because they can direct where chargers are installed, specify the capabilities the chargers have for communicating with utility systems, or require customer participation in load management or rate programs. For example, Holy Cross Energy's (HCE's) "Charge At Home. Charge At Work" program offers members a free Level 2 charger in exchange for automatic enrollment in the utility's distribution flexibility tariff (DFT). The DFT combines peak time rewards and dynamic renewable pricing to incentivize increased demand during times of anticipated oversupplies of renewable energy and load reductions during times of undersupply. In addition to the free charger, members receive monthly bill credits for participating in the DFT. Benefits to the utility beyond influencing charging behavior are that the utility knows where EVs are connected on their system (which is not a given), they have access to charging data, and the rate can encourage good charging behavior[104] [105]. Green Mountain Power (GMP) is offering potential EV customers rebates as well as financing, maintenance, and management to businesses to electrifying their car or bus fleets and electric vehicle load management programs. These are similar to traditional demand response programs, but they can go beyond that because of electric vehicles' unique nature to dynamically shift load both temporarily and geographically. For electric vehicle load management programs, customers are compensated for allowing the utility to adjust (or modulate) the charging speed, or to stop the vehicle charging altogether, during times of peak demand or system constraints. Compensation mechanisms that utilities are utilizing include gift cards or bill credits for a specified amount for particular intervals, often monthly or yearly. For example, GMP's program includes installing bi-directional Level 2 chargers, software, maintenance, and management to help reduce peak energy use and lower operational costs (GMP 2020). Through peak shaving, GMP expects this program could reduce overall costs to ratepayers (GMP 2020).

[104] Voices of Experience. An EV Future: Navigating the Transition, 2021: [Online]: https://www.smartgrid.gov/files/documents/An_EV_future_10.13.21_FINAL.pdf

[105] HCE, 2019. Holy Cross Energy Tariff Book. [Online]: https://www.holycross.com/wp-content/uploads/2019/06/Electric-Service-Tariffs-Rules-and-Regulations-amended-14May2019-CLEAN_a.pdf#page=38.

Static Rates



Technically, the most static rate is a flat rate, where a customer pays for how much electricity they use, but with no variation by time of day, week, or year. Since no change in behavior is incentivized, flat rates are not discussed here. There are several other static rates, such as Time of Use (TOU), Critical Peak Pricing (CPP) and others, that can be effective at shifting charging towards times or locations that coincide with available generation or distribution level power system needs. While the temporal influence is clear (cost of electricity varies throughout the day), the locational influence on EV owners is that depending on the rate, it may be cheaper to charge at work, or charge at home, thus incentivizing where and when electricity is consumed on the system. Customers can be extremely price sensitive, depending on economic status, personality, or other factors. Anecdotes abound about internal combustion engine vehicle owners' propensity to drive miles out of their way to save pennies per gallon on fuel costs. Given this price sensitivity, well-designed pricing (or rate) structures communicate when or where to charge, and cost savings can influence EV charging behavior to shift charging load in support of broader grid needs and to minimize system costs.

Implementation of any new rate structures is contingent upon state regulatory or utility governing board approval. Proactively working with regulatory bodies to develop rates that support EV integration through managed charging will be required to realize the potential for rates to support managed charging. TOU rates have been found to save consumers money while relieving stress on the electric grid, helping to delay grid updates by making better use of existing infrastructure.[106]

EV TOU rate options range from traditional static time-of-use rates, which have specific time blocks for on- and off-peak, to highly dynamic variable pricing in which the hourly electricity rate is based on both temporal and locational factors, discussed further in the Dynamic Rates section below. Static TOU rates with hard cut-offs between peak and off-peak rates are simple approaches that can provide effective charge management. However, without proactively managing the transition between peak and off-peak periods, static TOU rates have the potential to create "rebound" or "timer peaks" when the peak period ends and rates fall so customers start charging simultaneously, unless mitigations approaches are employed to stagger charging. Similarly, TOU rates for residential customers or demand charges for commercial customers could be used to incentivize owners of bi-directional EVs to discharge behind the meter and provide peak shaving for the utility as well as cost savings to customers.

Implementation of TOU pricing programs requires AMI and associated billing system investments. Depending on the rate structure, TOU rates can be applied to the whole home

[106] Voices of Experience. An EV Future: Navigating the Transition, 2021: [Online]: https://www.smartgrid.gov/files/documents/An_EV_future_10.13.21_FINAL.pdf

energy use or only to the energy use of the vehicle as measured and recorded by a submeter (see below for a further explanation on submetering). In 2020, 75% of U.S. households have advanced meters (The Edison Foundation, Cooper and Shuster); however, only 10% of electric utilities nationwide reported offering some form of time-based rate to their residential customers.[107] While the value of AMI has been demonstrated for enabling TOU rates, the presence of AMI doesn't guarantee that TOU rates will follow. TOU rates will require approval from regulatory boards.

TOU rate information could also be coupled with information on availability of or demand for renewable energy to address customer preferences. This could also help drive customer behavior; however, more research is needed to demonstrate the efficacy and potential impact. Additional software and communications would be needed to enable this collecting of information, thus adding to complexity. Implementation considerations of TOU rates are discussed in Section II.C.iii.

In addition to price reductions and incentives to encourage EV charging during off-peak hours, some energy companies (particularly in Denmark, the Netherlands, the United Kingdom, and California) are also offering bi-directional rates to compensate bi-directional EV owners for V2G such as discharging energy, providing capacity, or other grid services: regulation, spin/non spin reserve, voltage support, frequency regulation, etc. Incentivizing discharging is another approach to mitigate charging during on-peak hours as well as offsetting grid constraints that result from vehicle charging. However, deploying V2G economically requires understanding the local markets, supply of participating EVs, infrastructure, and aggregation. These bi-directional rates could be a first step in helping enable transactive energy services and inform future dynamic compensation schemes for V2G.

Pricing strategies for vehicle charging are still in their infancy and will evolve as utilities perform pilots that test new rate designs to test consumer responsiveness and the rate's effectiveness for achieving desired results. A review of 11 evaluation reports of electric vehicle rate offerings in the United States published between 2013-2020 found that most outcomes were for short-term (6 months – 2 years) pilots; there were very few system-wide rollouts. Pilots were evenly split between whole house rates and EV-only rates. The results showed that properly designed TOU rates can be an effective tool for managing when a customer charges their electric vehicle as shown in Figure II.15.

[107] EIA Form 861 in Schedule 6 Part C asks utilities to indicate whether or not they offer TOU, RTP, VPP, CPP, or CPR to residential, commercial, industrial, or transportation customers. No more detailed information is requested regarding the design of these rates.

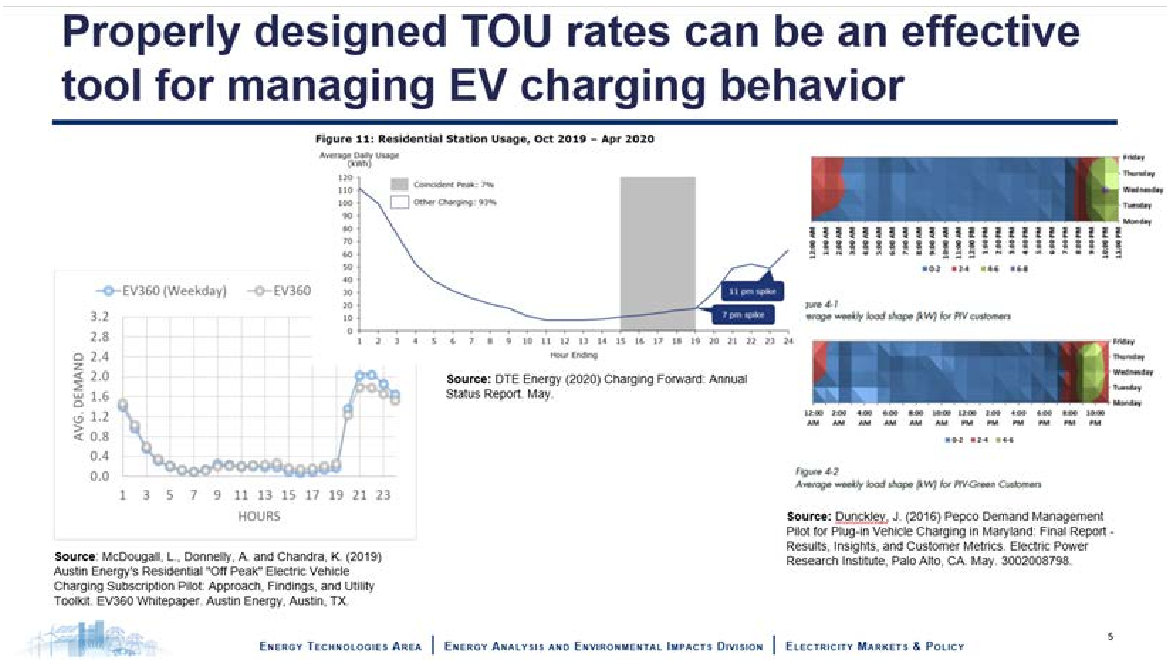


Figure II.40. TOU rate designs.

Results also showed that the higher the price ratio between on-and off-peak rates, the quicker customers learn to shift their charging to off-peak periods.

Participants in DOE's EV Future initiative corroborated the report evaluation results, reporting that initial findings show rates have been found to be good motivators for encouraging charging when grid capacity exits. For pilots of EV-only rates, initial results have shown that customers on residential EV-specific rates are more responsive with fewer opt-outs than for traditional demand response programs discussed above, such as for air conditioning[108], although final conclusions have yet to be made.

However, these pilot studies reflect early adopters of EVs, who likely have different motivations and preferences than might be exhibited throughout the broader driving public. Further analysis and evaluation are necessary to understand how these results may change and how robust these strategies to manage EV charging as additional consumers adopt EVs.

[108] Voices of Experience. An EV Future: Navigating the Transition, 2021: [Online]: https://www.smartgrid.gov/files/documents/An_EV_future_10.13.21_FINAL.pdf.

Examples of Utility TOU Rates

Burlington Electric Department (BED), in Vermont, offers a residential off-peak charging rate for customers who don't charge between 12:00 p.m. and 10:00 p.m. Customers who manage to avoid the specified hours for the entire month receive a bill credit that lowers the cost of fueling to the equivalent of buying gas for around 60 cents a gallon. There's no penalty for charging during the window, though. If the customer does, the regular residential rate applies. To receive the EV rate, customers must register their installed charger with BED and use one of two approved charger companies. Burlington found that uncontrolled home charging would add 20-60% peak contribution by a residential account. The EV rate has shifted almost all participant charging off-peak[109].

ComEd, An Exelon Company, received approval from the Illinois Commerce Commission's October 2019 and April 2020 Orders for a Residential Time-of-Day Pricing Pilot Rate.[110] The program launched in June 2020 and will run through June 2024. ComEd quickly met the pilot's participant cap of 1,900 in mid-December 2020.[111] As of March 2021, there were 164 self-identified EV customers. ComEd reported to the Commission that, as of March 2021, self-identified EV customers have saved nearly $10,000 over 9 months.[112] Without these incentives and communication upgrades to encourage charging at off-peak times, EVs would possibly strain the grid during peak times.[113]

Baltimore Gas & Electric (BGE) implemented an EV only TOU rate in May 2020 for residential customers with an eligible AC Level 2 charger (see Figure II.16). The rate's purpose is to provide EV owners with an incentive to charge their vehicles at times when there is excess capacity on the system and to make it easier for them to shift their charging during peak times. BGE found that customers on EV only rates are more responsive than whole home time-of-use rates in shifting vehicle charging. This is because, as the name suggests, with the EV only rate, customers need only focus on vehicle charging, which often can be managed through the vehicles on board systems or phone app; whereas, with a whole home time-of-use rate customers must be mindful of total energy consumption, which can be more challenging. Customers that have pools pumps running in the summer often did not benefit from the whole house rate. By the end of 2020, 60 customers had signed up, and after Tesla eligibility was added, enrollments increased to over 500 customers at the end of August 2021[114].

[109] Voices of Experience. An EV Future: Navigating the Transition, 2021: [Online]: https://www.smartgrid.gov/files/documents/An_EV_future_10.13.21_FINAL.pdf.
[110] State of Illinois, Illinois Commerce Commission. Order on Rehearing, 2020. [Online]: https://www.icc.illinois.gov/docket/P2018-1824/documents/298022/files/519662.pdf
[111] ComEd. Commonwealth Edison Company's Residential Time-of-Day Pricing Pilot Semi Annual Compliance Filing #2, 2021. [Online]: https://www.icc.illinois.gov/docket/P2018-1824/documents/310325/files/540776.pdf.
[112] *Id.* at 21.
[113] *Id* at 21-22.
[114] Voices of Experience. An EV Future: Navigating the Transition, 2021: [Online]: https://www.smartgrid.gov/files/documents/An_EV_future_10.13.21_FINAL.pdf

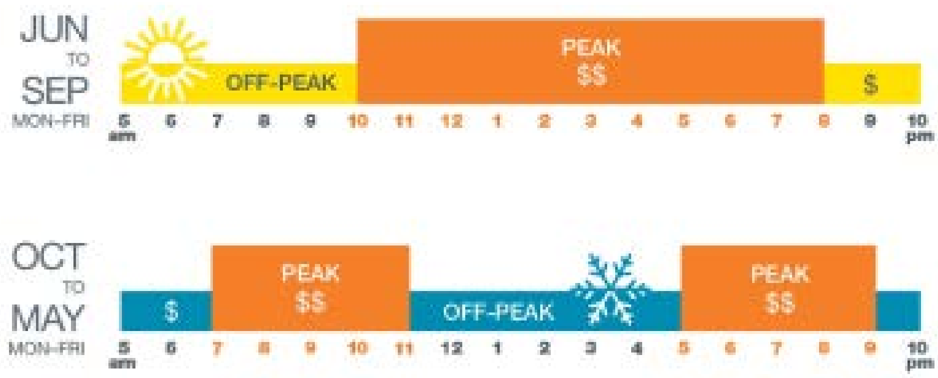


Figure II.41. BGE's TOU rate.

Dynamic Rates

Dynamic rates have much in common with static rates, but generally offer higher temporal or locational resolution, and therefore offer more control. One example of a dynamic rate is Real Time Pricing, where the price of electricity varies throughout the day, reflecting available generation or other system constraints. Highly dynamic rates, while more targeted, can have significant implementation costs and challenges. These dynamic rates may become easier and less costly to implement as the dynamic rates and assistive technology becomes more common. The effectiveness of rates and customer responsiveness to them, though, will require significant education to ensure that customers understand how they work and what it will mean for them (e.g., equating kWh pricing to terms that are meaningful and compelling). And the ability to participate will have to be simple, automated, and convenient. Full realization of these dynamic approaches will require corresponding modernization of utility rate data and documentation, including a basic standard for machine readable rates. Machine readable rates would enable customer and third-party software and hardware to internalize costs and react to changes with limited intervention from the customer themselves. While not common today, making rate information machine readable, as recently ordered in California, has the potential to improve both the customer experience and performance against the constraints these new dynamic rate targets.[115] It would also help enable a path to energy markets and transactive services at the distribution level, which do not currently exist. This would open the door for more sophisticated energy arbitrage activities and is a steppingstone for the grid services energy markets.

[115] California Energy Commission 2022 Load Management Standards Rulemaking Fact Sheet. https://www.energy.ca.gov/sites/default/files/2022-10/Load_Management_Fact_Sheet_ADA.pdf

San Diego Gas & Electric (SDG&E) offers a range of pricing programs from standard time-of-use plans to dynamic rates that change by the hour, as shown in Figure II.17. Their commercial Vehicle-Grid Integration Rate is an example of a highly dynamic rate that varies both temporally and spatially. It serves approximately 3,000 EV chargers in SDG&E's Power Your Drive program. The rate features a flat "base rate." On top of that is an adder for the California Independent System Operator (CAISO) day ahead energy price as well as hyper-local circuit peak adders that are applied during periods of peak system and circuit demand meant to be applied during the highest periods of grid demand. Customers can set a maximum price threshold they are willing to pay for EV charging on the utility's app. When the price of energy exceeds that rate, the vehicle stops charging until the price dips back below the threshold. These types of dynamic rates are most suitable for customer segments with long dwell times – where customers have their vehicles parked for long periods of time – so it is possible to move their vehicle charging around while still meeting the customer's charging needs[116].

EV-TOU	EV-TOU-2	EV-TOU-5	EV-High Power (proposed)	Vehicle-Grid Integration Rate
Residential EV TOU rate for separately-metered EV charging and some public charging	Residential EV TOU whole-house rate Otherwise identical to EV-TOU	Residential EV TOU whole-house rate with $16 fixed charge	Commercial EV TOU rate with subscription charge based on customer's preferred capacity	Hourly dynamic rate for workplace and multi-unit dwellings in SDG&E Power Your Drive Program
Less dynamic	←		→	More dynamic

Figure II.42. SDG&E's dynamic rates.

Sacramento Municipal Utility District (SMUD) is developing a rate for a commercial customer pilot that borrows from lessons learned by the California investor-owned utilities (IOUs) to address demand charge concerns and to comport with the business models and financial decision-making practices distinct to mobile asset fleet customers as compared to fixed asset facility customers. They are also ramping investments in RD&D and exploring partnerships with industry players, including cloud-based aggregators, to enable managed charging at the site level and to balance load across the network (SMUD RFI response.)

Submetering for EV Rates (for both Static and Dynamic Rates)

EV-specific rates are rates that bill customers solely based on EV charging usage. These rates require a meter, or submeter, to measure, record, and bill for the vehicle electricity usage separate from the premise usage. Billing determinants can be measured via the charger, the vehicle's onboard telematics, or by installing a second utility revenue-grade meter. There currently is not widespread agreement on a singular approach for submetering due to disagreements about the accuracy, certification requirements, data access, and cost implications.

[116] Voices of Experience. An EV Future: Navigating the Transition, 2021: [Online]: https://www.smartgrid.gov/files/documents/An_EV_future_10.13.21_FINAL.pdf

Accuracy and certification requirements for non-utility metering is at the center of submetering discussions that must be resolved. Utilities contend that responding to customer billing complaints will be difficult to defend if usage isn't captured using a utility meter, especially in litigated cases. Capturing data with the charger meter means that utilities will not have the ability to test the meter for accuracy or replace it if it isn't functioning properly. Therefore, some utilities advocate the installation for a second utility revenue-grade meter to provide visibility and control over managed charging solutions to ensure that the managed charging solutions benefit both individual customers and the energy grid as a whole. However, these additional meters add additional cost, and would likely eliminate the ability of customers to combine asset capabilities, such as PV generation or energy storage, in ways that shape aggregate consumption to customer and system benefit.

Some utilities are working with charger manufacturers on metering accuracy and have received state regulatory approval to bill customers based on charger provided usage data. Using the charger or the vehicle's onboard telematics lowers the cost of a second meter, which may be borne by the customer or socialized to all of a given utility's customers, and either approach could disproportionately impact low-income customers. According to Xcel Energy Minnesota, using the metering capability of smart chargers in lieu of a second meter saves customers an average $2,196 each in upfront costs. In August 2022, the California Public Utilities Commission was the first in the U.S. to authorize the use of charger-based submeters to measure and bill electric vehicle load separately from their utility meter.[117]

Demand Charges (for both Static and Dynamic Rates)

A customer's electricity rate can have two components: the volumetric charge, based on consumption (kWh), and the demand charge, based on the intensity of demand (kW). Demand charges are at the center of many discussions regarding electricity pricing for DC fast chargers for public chargers for light-duty EVs as well more generally for medium- and heavy-duty EVs. The demand charge is separate and in addition to the standard volumetric charge on a customer's bill. Southern California Edison has developed simple analogies to communicate the difference to their customers as shown in Figures II.18 and II.19 below[118].

One analogy is that of a car's speedometer, which measures the instantaneous speed of the vehicle, versus a car's odometer, which measures the distance traveled. The volumetric component of an electricity rate can be compared to the odometer. The volumetric rate bills customers based on their total consumption (using the car analogy, based on the odometer reading of the total miles traveled). The demand charge measures the intensity of the demand (in the car analogy, based on the speedometer reading of the vehicle's speed). As shown in Figure II.18, the demand on the car is more intense to travel 100 miles in 1 hour versus traveling 100 miles in 10 hours. This is similar for the grid as shown in Figure II.19. The demand

[117] California Public Utilities Commission, 2022. Decision Adopting Plug-In Electric Vehicle Submetering Protocol and Electric Vehicle Supply Equipment Communication Protocols, Decision 22-08-024. https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M496/K419/496419890.PDF

[118] SCE (Southern California Edison), 2021. Understanding Time-Of-Use Charges. [Online]: https://www.sce.com/business/rates/time-of-use/Understanding-Time-Of-Use-Charges

on the grid is more intense when burning ten 100-watt bulbs simultaneously for 1 hour than when burning one 100-watt bulb for 10 hours.

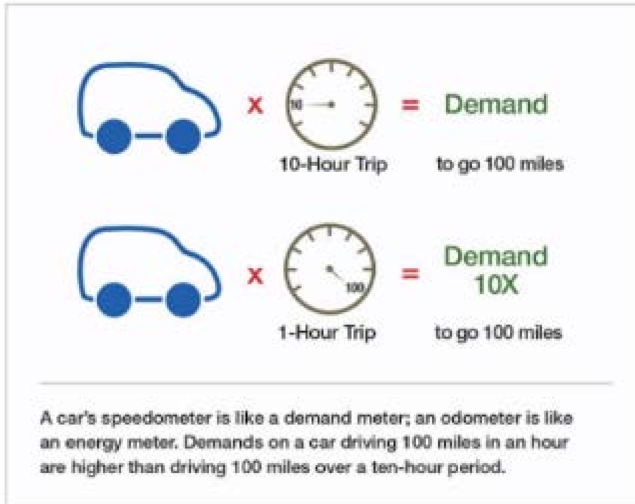


Figure II.43. Demand on the car.

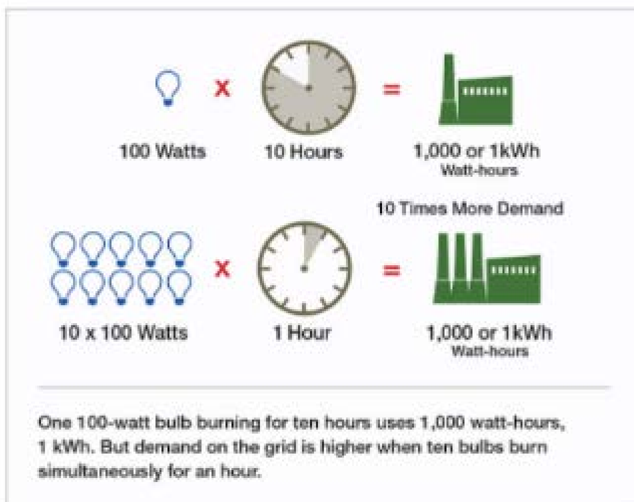


Figure II.44. Demand on the grid.

The demand charge was developed over a century ago to account for high intensity energy users as a mechanism for the utility to recover the costs of infrastructure investments even if the infrastructure is used infrequently. It is typically a component of a commercial electricity rate; however, a handful of utilities have implemented demand charges for residential customers. A customer's demand charge is based on the highest recorded load that the customer uses during a stated interval, which can range from 5 to 60 minutes, over a specified period, which can be from one billing cycle to, in some cases, 1 year. Demand charges vary from utility to utility and must be approved by state regulatory or utility governing bodies.

Demand charges can have a significant impact on charging station economics because demand charges can actually account for the majority of the operating expenses, and can, on their own, exceed the revenue generated. In fact, a single higher usage event can nullify a station's financial viability for the month, or even a year. Utilities see the demand charge as a critical mechanism that ensures electric rates are a cost causative price signal that aligns historical embedded infrastructure costs to customers with high instantaneous energy requirements.

Demand charges were developed based on building load profile characteristics and were designed to reflect the cost of building a distribution system capable of serving peak demand while incentivizing customers to consume energy at a consistent rate and to avoid peak times. When coincident with system peaks, utilities contend that pricing structures can encourage charging at times that will limit negative impacts. EV load characteristics, especially for high-powered chargers, are different from building load characteristics. They are pulsating loads and won't necessarily flatten out over time. It has raised question about whether the traditional demand charge structure fits the nature of EV charging. Discussions are taking place across the country to determine if the nature of electric vehicle charging warrants a different approach, and in the short term, some utilities and commissions instituted a pause on the application of demand charges for certain EV customer classes over a given number of years with the intention to reintroduce charges in phases while station utilization rates increase.

Mechanisms such as demand charge credits or temporary moratoriums, especially for circuits that are not near capacity, can support market development by improving station economics until the market can support higher utilization rates. Phasing them back in as utilization rise can reflect the temporary nature of the underlying issues related to low charger utilization. In Maryland, Exelon is piloting demand charge credits for new EV charger installations for non-residential customers that offers a reduced demand charge, or discount, of up to 50% of the nameplate capacity. Holy Cross Energy developed a TOU rate for transit authorities as part of its Electrify My Ride program. The cost is a four-to-one rate – 6 cents off-peak, 24 cents on-peak – and has no demand charge. Holy Cross Energy found that the rate also works well around the clock for DCFC stations with low utilization instead of the commercial rate that would impose a demand charge when the first electrons start flowing. The higher on-peak rate proves to be less costly than the standard commercial rate with demand charges. This remains true until a station handles around 280 charging sessions per month, at which point the station's utilization is high enough that Holy Cross Energy's demand charges are more beneficial than the higher on-peak pricing structure with no demand charges.

Technology, such as stationary battery storage, can help mitigate the impacts of demand charges, and charging network providers have begun to install onsite batteries that store energy during off-peak hours to later use to supplement demand during on-peak hours. However, Electrify America in their 2020 Annual Report[119] noted that this approach isn't universally seen as beneficial by utilities. Some utilities treat the battery as additional load

[119] Electrify America, 2020. 2020 National Annual Report to U.S. EPA. [Online]: https://media.electrifyamerica.com/assets/documents/original/684-2020ElectrifyAmericaNationalAnnualReportPublic.pdf.

rather than a tool to offset demand, which can lead to larger-than-necessary transformers, driving up station costs. It can also mean that interconnection costs for stations with batteries are more costly than for stations without them, creating a barrier for battery storage deployment as a demand mitigation strategy. However, in some jurisdictions, the battery paired with solar could help resolve concerns with treating batteries as additional load. Establishing a clear industry-wide standard for the treatment of battery storage for DCFC stations will be essential for advancing battery storage as a demand mitigation strategy.

Bi-directional EVs and bi-directional EV charging infrastructure connected to certain loads (e.g., commercial buildings) could also help mitigate the impacts of demand charges. This has been piloted in a few locations in the United States and is seen as a potential new revenue stream for EV owners that may offset battery degradation in certain markets. Bi-directional EVs connected to loads subject to demand charges can participate in energy arbitrage activities to create value for bi-directional EV owners and connected loads. However, more research is needed to confirm the costs benefits and variation in battery degradation that is expected and dependent on the electrochemistry of batteries. See Section II.C.vi. for a more detailed discussion on opportunities for bi-directional EVs to monetize demand charge programs.

Grid Service Markets

There are grid control and balancing issues, both at the transmission level and at the distribution level, that cannot be anticipated sufficiently in advance to incorporate into an electricity rate formula. In addition, the lowest cost to address that control requirement also cannot be determined, in that hundreds or thousands of assets could feasibly address it. Where the buyers in the market don't know what the lowest cost for a service could be, and the sellers of the service don't know how much they could charge, a market is a good option. A market is simply a method for matching buyers and sellers in a way that solves both problems at the same time. Markets are desirable because they are economically efficient, but they are complex and costly to establish relative to a rebate or static rates and require that participants have sufficient capability to participate. In the absence of market options, the solution to concerns about insufficient control or satisfying energy needs is to install utility-owned physical assets capable of handling all potential loads and exerting all the necessary control without reliance on anyone.

Markets are relatively mature in the generation and transmission domain, with competitive markets for multiple grid operational services, such as capacity, energy, frequency and ramping, called wholesale markets. Market participants must meet certain requirements, and customer owned resources, even as substantial as EVs, are generally excluded from competition. Direct participation in wholesale electricity markets can open up opportunities to increase value of electric vehicles. One area that could result is the emergence of third-party aggregators that offer options for customers. Aggregators may offer solutions that control EV loads and aggregate with other EVs – and even other types of DERs – to participate in demand response or other programs such as a result of FERC's landmark Order No. 2222 in 2020[120]. Compliance with FERC 2222 is an incremental process, but as opportunities for responsive assets develop, EVs can be well positioned to take advantage of them for their owners' benefit.

Grid service market opportunities are not limited to the wholesale market. In the same way that FERC has acknowledged that DERs, such as EVs, have value in economically addressing constraints in generation and transmission, distribution systems can solicit grid services through market mechanisms. Today, grid service needs at the distribution level are served almost exclusively by utility-owned assets, such as voltage regulators, capacitor banks, and other system hardware and software, or by generation and transmission systems. Distribution systems face more stresses today, stemming from increased weather-related events, new distributed clean generation, customer and third-party storage, and society's increasing reliance on electricity. In the case of flexible DERs, and especially in the case of mobile DERs such as bi-directional EVs, incentives have the capacity to coordinate DERs to alleviate stress and actually increase the resilience, reliability, and controllability of the grid. Many of the grid services needs of the grid are location or time dependent, and so any transactions that might incentivize coordination must be similarly fluid. Techniques used to address this need are therefore called transactive control or transactive energy.

With so many potential sources of flexibility available to the grid today, it doesn't make sense to establish grid services markets for a single asset, whether it's PV, pool pumps, or EVs. Utilities already make efforts to treat DERs more generically in simpler demand response programs using software platforms called DERMS. Grid service markets would approach optimization of bi-directional EVs and other DERs in the same manner, with the addition of dynamic market mechanisms to facilitate transparent and competitive solicitation of grid services from all sources of flexibility. Markets also ensure that the right of customers to operate their assets as they see fit is respected, and that their participation is possible where appropriate, voluntary, and properly compensated. Grid services markets are clearly more complex than other incentive options, with attendant higher implementation and operations costs. Their advantage is that utilities gain access to fine grained control with respect to location and time that specifically address their needs, and customers find more compensation opportunities for their excess flexibility. If the customer has a better use for their EV, they don't sell their flexibility; if the utility does not need flexibility at that time and location, they don't buy it. The intent of this class of incentives is to increase the potential for optimization of all energy assets to the benefit of all participants.

Transactive control, FERC 2222 mandated DER markets, and other potential grid services markets are not mature. Also, significant work is needed to transact grid services at the distribution level. As mentioned earlier, energy markets currently only exist at the transmission level. There is active RDD&D in this area by DOE and others in the United States, but also in the

[120] https://www.federalregister.gov/documents/2020/10/21/2020-20973/participation-of-distributed-energy-resource-aggregations-in-markets-operated-by-regional

Netherlands, the United Kingdom, Australia, and elsewhere. Electric vehicles have unique capabilities that could benefit their owners as well as the grid, potentially allowing higher penetrations at lower infrastructure costs, maximization, and optimization of renewable energy, and will be the subject of further research by DOE and others. These sophisticated approaches will require market mechanisms to monetize the value to consumers and will require supporting policies.

It should be reiterated that no one class of incentives, whether one-time payments, rates or grid services markets, eliminates the need or usefulness of the others. Rebates, rates, and markets should be thought of as a layered approach, with each layer added or enhanced only when required and beneficial to all participants. Some customers may forego a rebate and buy the EV or charger they want and participate in a simple TOU rate. Some utilities may see a high DER future and embrace grid services markets to balance and optimize their system and incentivize customer participation such that all their needs are met. Incentives are a powerful tool, but the recipe for success will vary across the country.

Takeaways

A portfolio of incentive options will be necessary, but as significant EV adoption develops, it may require more sophisticated approaches that include locational and temporal elements and can provide more refined control and dispatching strategies.

Establishing incentive signaling early in the EV adoption path establishes customer expectations that are critical to behaviors necessary to support high EV penetrations.

The increased value of more sophisticated incentive approaches will have corresponding increases in costs and complexity, but in some cases the value may far offset the costs.

Customer behavior can be unpredictable and how they will respond is still unclear and requires additional research. Early adopters' behavior, and findings based on their behavior, might not represent behavior of the general population.

The customer experience with incentives should be easy and seamless. Education will also be important for effective pricing implementation, customer preferences (e.g., signaling when renewables are dominant on the grid or in need of demand), and customer satisfaction.

Rates can be an effective mechanism for incentivizing customer behavior but require advanced metering infrastructure to implement.

Addressing customer preferences via highly varying rates will require availability of dynamic information and automation to meet those preferences, and those information needs will propagate across other actors in the system.

Transactive energy markets do not currently exist at the distribution level where more complex approaches, such as real-time pricing or grid service markets, will likely be necessary.

Recommendations

DOE could expand activities to provide technical assistance to stakeholders to improve local and regional EV adoption tools across light-, medium-, and heavy-duty classes that incorporate forecasts for anticipated grid impacts and can assist in development of appropriate incentives that balance grid and customer benefits.

- DOE could expand activities to advance information usability for customers and other stakeholders through development of machine-readable incentives such that software and people can easily incorporate incentive signals into their behavior.
- In collaboration with stakeholders, DOE could perform research to inform the design of equitable rates and incentives that are attractive to future customers and grid operators.
- DOE could develop and demonstrate optimization algorithms to assist with development of dynamic pricing incentives and transacting V2X at the distribution level.
- DOE could evaluate tools and strategies as well as conduct demonstration projects to mitigate information asymmetry across key system actors to help facilitate customer preferences (e.g., prioritizing carbon-free generation) and leverage incentives for transactive services.
- DOE could expand activities to conduct demonstration projects to evaluate and help address regulatory, policy, and market barriers that would allow for development of effective incentives to utilize EVs to provide load flexibility for bulk power and distribution system services.
- DOE could expand activities to support development of a standard specifically for metering EV energy usage, to allow for development of EV incentive structures, that is recognized and accepted by utilities and other entities, especially in areas with special rates, programs (including low income assistance programs), or controls for those EVs.
- DOE could provide assistance in valuation of SCM capabilities and financial mechanisms that enable market access (e.g., compensation mechanisms).
- DOE could evaluate and advance commercialization strategies and tools, and conduct demonstration projects to reduce barriers to V2X such as enabling third-party aggregation, evaluating innovative ownership models, streamlining interconnection, reducing interconnection costs where possible, and other business models, valuation, policy, and other protocols, etc.

vi. Technology needed to achieve bi-directional power flow on the distribution grid

Bi-directional power flow from electric vehicles can enable many potential applications, such as providing grid services like voltage or frequency regulation, providing load shifting capabilities to a utility, vehicle owner, or building owner to offset demand charges, as well as potentially providing backup power to the vehicle owner's home or to a building where the vehicle is parked. To enable and leverage this potential, the proper equipment and controls must be available at the vehicle and/or premises to achieve the bi-directional power flow onto the distribution grid. In addition, the connecting grid must have the capability to accept the power, and an interconnection agreement must be approved and in place. Hardware for grid upgrades may be needed to handle V2X (see II.C.I). An interconnection agreement is required for bi-directional flow of power back to the grid for any DER service including electric vehicles. The interconnection agreement must be approved by the utility, who establishes the process and determines the cost based on the framework approved by the PUC. In this developing area, there is concern with asymmetrical utility information and influence on the interconnection process for DER in certain jurisdictions. This lack of uniformity creates significant challenges to deploying V2X capable EVs. Deploying V2X capable EVs primarily involves EVs with bi-directional inverters, V2X capable EVSE, as well as software and controls to safely dispatch energy, forecast, optimize, and securely transact services with the grid. Figure II.20 illustrates the primary elements to enable an electric vehicle to serve as both a mobility and energy asset.

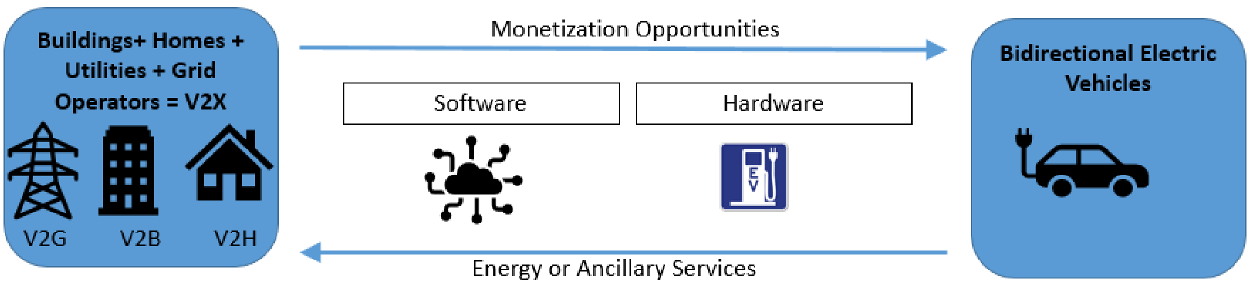


Figure II.45. Primary elements needed for V2X integration and interactions.

EVs that are V2X capable have unique capabilities compared to EVs that provide only V1G grid services. These V2X-capable EVs can discharge electricity back to the grid, such as when renewable generation is low, in addition to its normal charging capability as a load on the power grid. Thus, these V2X-capable EVs are providing additional capacity and more specialized flexibility that could help defer system upgrades, as well as optimizing and maximizing carbon-free generation. They can also provide backup power to a home or building. Although the immediate interaction is with the electricity distribution network, as adoption rates increase, the impact of V2X-capable EVs would expand from the distribution grid to the transmission grid, and the corresponding wholesale electricity markets (see Section I.B)[121].

Additional system integration tools/software on the grid would be required to aggregate and optimize integration. This could include tools such as ADMS and DERMS to communicate with the transmission and/or distribution system operator (if there are energy markets on the distribution grid). The impact could range from short-term grid operations to deferral of long-term generation and transmission capacity expansion (as one of many DER options) and could help ensure adequate capacity for large-scale future V2X-capable EV adoption using market forces. However, the behavior of EVs and their owners requires more research to determine the adequacy and reliability of this resource. For example, an EV could charge when electricity prices are lower and sell electricity by discharging when prices are higher. Therefore, with the right tools and access to energy markets, EV owners can make revenue or offset total charging

[121] Zhou, Yan, Muehleisen, Ralph T., Zhou, Zhi, Macal, Charles, and Oueid, Rima. Considerations for Building the Business Cases for Bidirectional Electric Vehicle Charging. United States: N. p., 2021. [Online]: https://publications.anl.gov/anlpubs/2021/08/170073.pdf.

costs by arbitraging the prices[122]. Note, that as part of the Integrated Resource Planning (IRP) process, DER is being examined as part of generation and transmission expansion planning.

Currently, bi-directional power flow in electric vehicles only exists in demonstration projects, or niche deployments in the United States. Many U.S. utilities are still trying to evaluate what bi-directional charging may provide, how to implement it (both technologically and from a regulatory perspective), as well as how to properly incentivize it against the impacts to the primary EV transportation mission (e.g., customer behavior) and battery life. This also raises questions regarding different ownership models that could better enable and incentivize V2X-capable EVs, some of which are discussed later in this section. The underlying capability has been demonstrated, but often in limited numbers or with limited production equipment. Major LDV manufacturers have started forays into the V2X space, such as the Ford F-150 Lightning truck or demonstration projects with the Nissan Leaf but are still in limited deployments and capabilities in the United States. However, there is significant V2G activity abroad. For example, Nissan has an agreement with Tokyo's Nerima Ward and the city of Yokosuka to provide V2X-capable EVs for emergency situations (discussed further later in this section). In 30 European countries, Virta is working with utilities and businesses with fleets to deploy V2G hardware and software. Virta currently has 170,000 chargers deployed, with approximately 300 partners (Virta 2021). For MDV and HDV populations, there are several demonstration projects using V2G-capable school buses in the U.S. Specifically, Dominion Energy is deploying 50 V2X-capable electric school buses in Virginia and 60-kW bi-directional DC chargers to demonstrate the performance and business model for V2G in a real-world setting (Dominion Energy 2020).

Many of these demonstration projects have evaluated the use of EVs for grid services, including bi-directional charging. Other current capabilities have a primary focus on providing backup power to an islanded site or building (V2B, V2H), avoiding any interconnection issues and direct grid impacts. Many of these projects can be broken down into behind-the-meter capabilities (backup power, use as storage for customer DERs, or peak shaving to reduce demand charges for connected loads) versus front-of-the-meter capabilities (grid services, coordination and/or aggregation over multiple customers/households/etc.).

Challenges/Needs

While there are many opportunities for bi-directional power flow from electric vehicles, technological barriers need to be addressed for large-scale adoption to occur. One significant challenge is the standardization of the various aspects of the bi-directional power flow process. Much of this standardization is directed toward the standards efforts detailed later in this report (Section II.D). This focuses on standardized connectors and communications schemes between the charging service provider, the EVSE, and the EV itself. Efforts are being made with the ISO 15118, SAE 3072, UL 1741 and updates to the California Rule 21 guidance, but these are still evolving and not all OEMs have achieved consensus on adopting these standards.

[122] Zhou, Yan, Muehleisen, Ralph T., Zhou, Zhi, Macal, Charles, and Oueid, Rima. Considerations for Building the Business Cases for Bidirectional Electric Vehicle Charging. United States: N. p., 2021. [Online]: https://publications.anl.gov/anlpubs/2021/08/170073.pdf.

There are challenges with DC bi-directional charging due to high cost and limited availability of low-power, V2G-capable, residential DC EVSE. There are only a couple of U.S. companies offering DC-based residential V2G-capable chargers which currently cost more than AC Level 2 chargers. There are also challenges associated with AC bi-directional charging due to the need for EVs to have onboard bi-directional inverters, as well as communications and controls with AC EVSE (which is necessary to provide V2B/V2H capabilities). This adds size and weight for EVs to achieve AC-based bi-directional power compatible with a V2X-compliant AC Level 2 EVSE, which meet UL 1741. As a result, AC-based bi-directional EVs would cost more than DC-based bi-directional EVs. Therefore, the feasibility of residential AC-based V2G compared to residential DC-based V2G should be examined.

Another key element of standardization expressed in the RFI responses is on the grid interconnection side. While minor details could vary from utility or interconnect, bi-directional charging does not have an over-arching standard like other DER technologies (e.g., IEEE 1547). Some standard guidance is needed from a vehicle and/or EVSE OEM perspective, to ensure they don't need 50 (or more) different firmware versions to accommodate every state's or utility's different interconnection requirements. In addition, while standards are being developed related to control of grid-connected devices and for the general transaction of energy, incorporation of standards (such as safety and interoperability) to include the use of V2X-capable EVs as mobile storage for buildings is needed. Also, more research is required to continue to reduce equipment costs for revenue-grade metering and controls and to help get these technologies to market which benefit both V1G and V2G[123].

Even with a proper technology solution developed, the sequencing of deployment can be another significant challenge. To accommodate bi-directional power flow to the grid, especially if V2X capabilities are integrating with larger DER frameworks, infrastructure updates and system improvements may be needed that may require long timelines to complete in some regions. However, where capacity constraints exist at the distribution level, V2X-capable EVs could be a DER asset and help offset some infrastructure updates. With significant populations of V2X-capable EVs and other DERs, coordination between the devices will be very important. This is especially important in areas where providing grid services may be most beneficial, such as at the end of longer radial distribution or transmission lines, in islanded microgrid scenarios, where there are distribution grid capacity issues, or where there are resilience concerns on the transmission or distribution system. Figure II.21 visualizes some of the complexities required for controlling more advance power grids, including highlighting where the capabilities of V1G and V2G are really needed.

[123] Zhou, Yan, Muehleisen, Ralph T., Zhou, Zhi, Macal, Charles, and Oueid, Rima. Considerations for Building the Business Cases for Bidirectional Electric Vehicle Charging. United States: N. p., 2021. [Online]: https://publications.anl.gov/anlpubs/2021/08/170073.pdf.

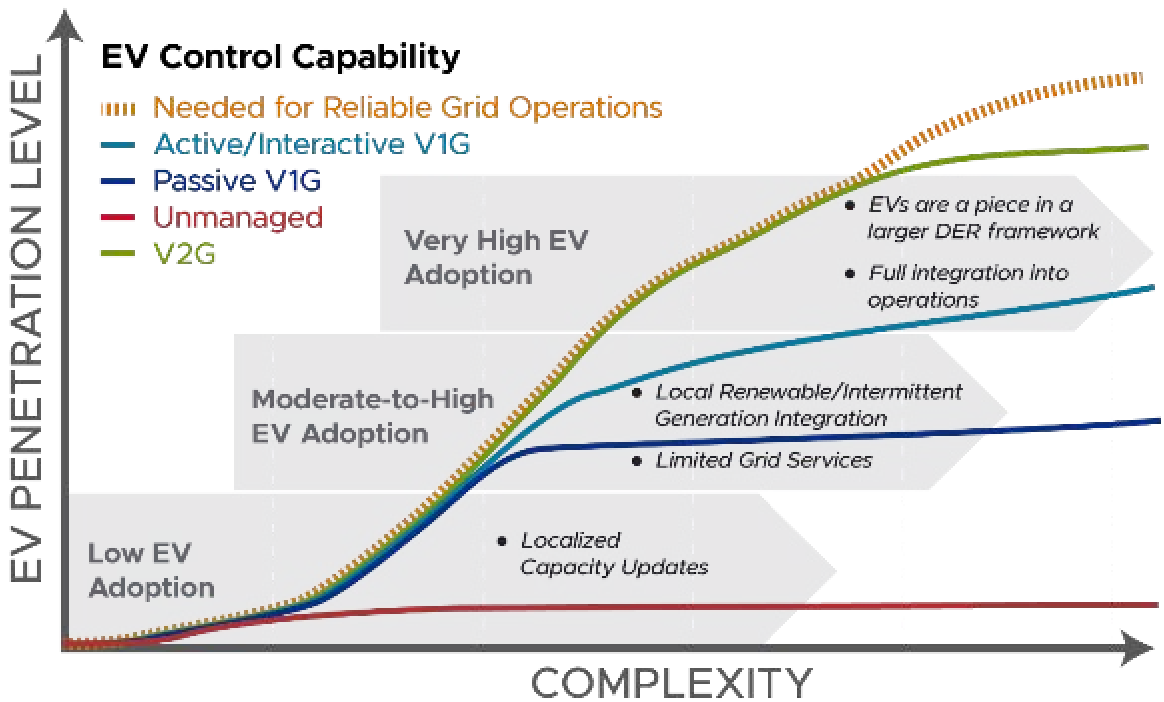


Figure II.46. Required control capability for increased EV penetration levels.

It is worth noting that aggregation is most often required for scenarios like this to fully monetize the bi-directional power flow capabilities. DERMs could help with coordination with an aggregator of V2X EVs that could be dispatched. In terms of execution, this creates technological (both on the electrical interface side and communications/cybersecurity side) and regulatory opportunities and challenges.

To enable aggregation for V2G, communications and control software will be needed at multiple levels, behind the meter and in front of the meter (at the distribution and/or transmission level). The different software packages provided by multiple vendors need to be compatible to enable V2X capabilities. This software should enable access to energy markets. Existing DER integration approaches, such as distributed solar and distributed storage deployments, can be leveraged to develop these capabilities.

Opportunities

On average, passenger vehicles are parked 95% of the time[124]. In addition, passenger vehicles are most often parked in or near structures such as homes, buildings, garages, or parking lots, thereby enabling opportunities for those vehicles to be connected to building electrical systems if V2X-enabled EVSE have been installed in those locations. Although not all vehicles have long dwell times or will be parked with access to an EVSE[125], there is a significant subset of the

[124] Schoup, D. 2018. The High Cost of Free Parking (Updated Edition). Routledge.
[125] Ge, Simeone, Duvall, and Wood. 2021. *There's No Place Like Home: Residential Parking, Electrical Access, and Implications for the Future of Electric Vehicle Charging Infrastructure*. NREL Technical Report NREL/TP-5400-81065. [Online]: https://www.nrel.gov/docs/fy22osti/81065.pdf.

population that have a long dwell time and could participate in V2X programs. Further research is needed to address issues related to monetizing the battery and to ensure enough power remains to complete driving tasks. Additional research is also needed to determine how EVSE access could be improved through electrical infrastructure and parking behavior modifications to help increase the number of idle vehicles that could participate in V2X opportunities. As mentioned earlier, buildings participating in demand response programs can use power from V2X-capable EVs to reduce their demand charges as a peak shaving strategy. There is increasing interest in this use case today in the United States because it can be deployed behind the meter where there are fewer hurdles to implementation.

There may be opportunities for all EVs to be incentivized to charge their batteries while parked during the day to avoid curtailment of renewable energy. V2X-capable EVs can be further incentivized to access that power at home or discharge to the grid during grid peak demand times, thus simultaneously smoothing the duck curve and decreasing greenhouse gas emissions. Moreover, V2X-capable EVs can potentially be used as a source of backup power for the homeowner when the grid goes down by storing power from the grid prior to the blackout, and/or enabling onsite carbon-free generation to continue to operate. This could address customer preferences and provide a level of resilience many residences would value during grid blackouts.

Similarly, opportunities exist for medium- and heavy-duty vehicles and fleets such as buses, refuse trucks, and delivery trucks. Given the primary purpose for these vehicles is to transport goods and people, or provide services (e.g., removing waste), more analysis is needed to quantify the duty cycles and potential value that could be derived from monetizing V2X-capable electric MDVs and HDVs when they are idle. The duty cycles for some of these fleets may provide enough monetization opportunities that could help offset the cost of electrification of these fleets. There are many use cases that warrant further study for both passenger vehicles, fleets, and MDVs and HDVs[126].

The examples above could create value to end users, as well as society (e.g., to support homes, buildings, or critical infrastructure such as hospitals and nursing homes), if the right incentives and market platforms are present, thus creating unique opportunities. However, similar to the discussion in Section II.C.iii, more analysis is needed to prepare for customer charging, as well as discharging, behavior in the days or moments before and during a known grid disruption. This may require additional technologies or protocols.

V2X-capable EVs could provide an array of ancillary services that support grid operations through aggregation and enabling hardware and software technologies, such as DERMS. Recall from Section I.B.iii.c the various types of fundamental DER grid services, which are listed below with the opportunities of bi-directional power flow from electric vehicles outlined. It is important to remember that these DER grid services may be aggregated or leveraged by both the transmission and distribution system to provide “traditional” grid services (such as

[126] California Public Utilities Commission (CPUC) Vehicle Grid Integration Working Group 2020. Materials Produced by the VGI Working Group – Methodology Development. [Online]: https://gridworks.org/materials-produced-by-the-vgi-working-group/.

arbitrage, types of reserves, etc.). Figure II.22 provides a visual representation of the grid services V1G and V2G-capable EVs; it is important to note that only V2G can provide black start capabilities. For the other services, V2X-capable vehicles may be able to provide a greater magnitude of the service, depending on the grid condition, availability of the vehicle to participate, and controls implemented. More research is needed to properly quantify the cost and benefits of V1G and V2G grid services.

	Energy Schedule	Reserve	Regulation	Black Start	Voltage or Volt/Var	Frequency Response
V1G	✓	✓	✓		✓	✓
V2G	✓	✓	✓	✓	✓	✓

Figure II.47. V1G vs. V2G DER Grid Services Capabilities.

Energy Schedule Service: consume or produce a specified amount of energy over a scheduled period of operation. Bi-directional power flow (V2G) enables the EV to actually produce power (discharge) for this grid service, whereas uni-directional power flow (V1G) could only adjust the consumption rate. This type of grid service provides capacity and enables energy arbitrage opportunities.

Reserve Service: reserve some capability for increasing power generation or shedding load and act upon grid operator's signal within a short timeframe (e.g., 10-30 minutes) when dispatched in a contingency. Bi-directional power flow enables the EV to actively inject power back into the system and provide a larger range of benefit over merely increasing or decreasing the charging load to provide the reserve service.

Regulation Service: increase or decrease real power generation or demand against a predefined kW base point following the grid operator's automatic signal every few seconds. Bi-directional power flow enables a larger range of regulation services, due to being able to both charge and discharge into the grid.

Black Start Service: start without an outside electrical supply and energize part of the electrical power system. Bi-directional power flow capabilities can explicitly enable this, utilizing the EV as energy storage to provide power to critical assets or be used to help restart larger power system operations. In a broader sense, this may be more oriented toward restoration actions and not the explicit black start of thermal plants at the transmission level.

Voltage or Volt/VAR Service: inject or absorb active or reactive power (or increase/decrease active/reactive loads) to correct excursions outside voltage limits. Bi-directional power flow enables active power to be released back into the grid as a way to adjust local voltage, which could be useful when the reactive power capabilities of the power electronics are not sufficient.

Frequency Response Service: detect frequency deviation and instantly inject (or absorb) active power to help arrest the frequency drop (or increase). Bi-directional power flow allows for a single EV to provide greater range of deviations, being able to discharge into the power grid as an energy storage device.

V2X-capable EVs provide capacity and flexibility such that they can act as DER and be deployed in an array of use cases, which includes grid services, thus providing more capacity, reducing grid congestion, and helping to defer infrastructure upgrades. V2X grid services are discussed in more detail along with V1G in Section II.C.ii. However, it is also important to discuss customer-specific use cases that could be addressed with V2X-capable EVs. Although the transmission system and distribution system use cases capture activities in front-of-the-meter, the customer use cases capture activities behind-the-meter. The following summarizes the key customer use cases that have been discussed for V2X:

Backup Power – during a grid blackout, V2X-capable EVs and their EVSE, paired with a local onsite generation, can provide backup at homes, buildings, or other loads.

Increased PV Self-Consumption – customers with V2X-capable EVs can maximize behind-the-meter PV systems for personal use and minimize export of electricity to maximize the financial benefit of solar PV in areas with utility rate structures that are unfavorable to distributed PV (e.g., non-export tariffs) (Fitzgerald et al., 2015).

Demand Charge Reduction (applies to buildings or commercial properties) - EVs can discharge energy via V2X-capable EVSE connected to buildings to help reduce their energy load on the grid and avoid demand charges imposed by utilities and based on the maximum amount of power a customer used in any interval (typically 15 minutes) during the billing cycle. (Brown 2017).

Time Shifting Charging and TOUs – both V1G and V2G can minimize electricity purchases during peak electricity-consumption hours when TOU rates are highest and shift purchasing to periods of lower rates, thereby reducing their energy bill (Fitzgerald et al., 2015).

Energy Arbitrage – V2X-capable EVs can purchase electricity during periods of lower rates and discharge electricity when electricity prices are high to generate revenue. They could also provide grid services but may need to be aggregated to meet a minimum capacity.

Individually or in aggregate, these customer use cases could help reduce the total cost of ownership (TCO) of an electric vehicle and/or provide revenue to the customer if there is market access[127]. TCO is a metric often used to quantify the cost of purchasing and operating the vehicle as an owner or fleet manager. TCO includes vehicle cost and depreciation, financing, fuel costs, insurance costs, maintenance and repair costs, taxes and fees, and other operational costs[128].

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[127] Zhou, Yan, Muehleisen, Ralph T., Zhou, Zhi, Macal, Charles, and Oueid, Rima. Considerations for Building the Business Cases for Bidirectional Electric Vehicle Charging. United States: N. p., 2021. [Online]: https://publications.anl.gov/anlpubs/2021/08/170073.pdf.

[128] Zhou, Yan, Muehleisen, Ralph T., Zhou, Zhi, Macal, Charles, and Oueid, Rima. Considerations for Building the Business Cases for Bidirectional Electric Vehicle Charging. United States: N. p., 2021. [Online]: https://publications.anl.gov/anlpubs/2021/08/170073.pdf.

To enable bi-directional-capable EVs to provide these opportunities and benefits, the technology and business models require further and continual development. Larger-scale demonstration projects are needed to help explore these aspects. DOE could partner with vehicle and EVSE OEMs, utility partners, and V2G service providers/aggregators to explore and evaluate different aspects of this. This would include assisting in the development and evaluating the technologies and communications to provide the bi-directional-based services, including their larger-scale impacts and benefits to the electric grid. The analysis can also assist in evaluating the effectiveness of different business models, particularly in assisting with electric utility acceptance and a valuation of the larger grid impacts. Because these grid services have been enabled by FERC order 2222, it would be useful to determine the necessary V2G systems technologies' costs targets (for EV and EVSE) that would make selling back-fed power at wholesale market prices (for grid services) viable for EV and EVSE owners.

As mentioned earlier, V2X introduces new opportunities for bi-directional EV owners and will vary depending on the type of customer and their primary motivations. Additional software and optimization algorithms could enable fleet owners to plan in advance or decide in real-time between a menu of options for how best to monetize their V2X-capable EVs when not transporting people, goods, and/or services. As discussed, V2X could be used to shift load and discharge back to the grid to help meet demand during peak periods. Companies such as Virta provide financing and ongoing support to monetize V2G capabilities to customers in Europe. Many of their customers are fleet owners trying to maximize monetization opportunities of their V2G-capable EVs. This type of customer behavior needs to be further studied to ensure we are optimizing system benefits (e.g., providing incentives and market platforms that increase utilization of carbon-free generation to power EVs where possible while maintaining a reliable, resilient, and affordable energy system).

There are unique opportunities to utilize DOE RDD&D to inform strategies and new business models that could help achieve V2G, as well as other DOE mission objectives. As discussed in II.B.I, artificial intelligence and machine learning was briefly explored to forecast and potentially mitigate battery degradation from V2X-capable EVs and accelerate access to information for manufacturers and insurance companies as they develop appropriate warranty coverage terms for V2X-capable EVs' batteries. This could also inform automakers, battery manufactures, third-party aggregators, and other finance entities or companies that would like to explore innovative business models, such as leasing schemes that allow the EV battery to be monetized and offset the cost of battery degradation. For example, Maryland's Montgomery County approved a 16-year, $169 million contract to lease 326 V2G-capable electric buses, part of a plan that may replace its 1,422-bus fleet over the next two decades. By leasing the buses rather than buying them outright, the county avoids the upfront cost of electric vehicles; the lease contract costs the same amount as the school system would otherwise spend purchasing, fueling, and maintaining new diesel-powered buses. The lessor plans to offset the contract cost through operational savings from an electric drivetrain and by monetizing the bi-directional capabilities of the electric buses[129].

A holistic understanding of the complete V2X-capable EV life cycle is required. The leasing arrangements mentioned above could involve a third-party retaining ownership of the entire V2X-capable EV, or just the vehicle's battery, and leasing only the body of the EV to the vehicle end-user. These leasing arrangements could help scale V2X deployment by reducing upfront costs for EVs. In addition, these arrangements could also streamline opportunities for new battery end-of-life deployments, which provide other benefits because these batteries can be recycled and reused. A deeper discussion on the potential for the reuse of spent electric vehicle batteries for stationary grid storage is covered in Section II.A.ii[130].

Takeaways

- V2G capable EVs provide additional grid services potential. However, the customer and vehicle manufacturer benefits must be present in order for these opportunities to exist.
- V2X capable EVs could provide backup power, black start, and restoration services.
- The basic technology has been proven and pilot commercial offerings are becoming available. However, commercially-available, certified products and the business model are still being developed and warrant further investigation.
- Bi-directional capability is currently enabled only through the DC charging connections, which are expensive and limited in availability in the U.S. This also requires associated hardware to be deployed at any desired V2X site, while bi-directional capability through the AC connection may enable greater flexibility in the location where this can be applied to the power system but increases the size, weight, and cost of EVs.
- More research is needed to confirm the value of monetizing V2X capable EVs and the trade-offs to battery degradation.
- V2X capable EVs could be used to help maximize and optimize renewable energy usage[131].
- A holistic understanding of the complete V2X capable EV life cycle is needed.

Recommendations

- DOE could conduct RDD&D and help commercialize technologies (e.g., leveraging Artificial Intelligence/Machine Learning) to optimize V2X, including dynamic pricing and transacting V2X at the distribution level.
- DOE could expand activities to conduct research to confirm the value of monetizing V2X capable EVs and the trade-offs to battery degradation. Work with vehicle OEMs to

[129] Zhou, Yan, Muehleisen, Ralph T., Zhou, Zhi, Macal, Charles, and Oueid, Rima. Considerations for Building the Business Cases for Bidirectional Electric Vehicle Charging. United States: N. p., 2021. [Online]: https://publications.anl.gov/anlpubs/2021/08/170073.pdf.
[130] Zhou, Yan, Muehleisen, Ralph T., Zhou, Zhi, Macal, Charles, and Oueid, Rima. Considerations for Building the Business Cases for Bidirectional Electric Vehicle Charging. United States: N. p., 2021. [Online]: https://publications.anl.gov/anlpubs/2021/08/170073.pdf.
[131] Tuffner, F, Kintner-Meyer, M. Using Electric Vehicles to Meet Balancing Requirements Associated with Wind Power, 2011.

address warranty concerns regarding potential battery degradation from bi-directional operations.

DOE could conduct techno-economic analysis to identify thresholds to inform viable V2G business models for wholesale market grid services.

DOE could expand activities to conduct RDD&D to maximize and enable optimal use of renewable energy sources by leveraging V2X capable EVs.

DOE could expand activities to assist in large-scale pilot programs to evaluate V2X business models, market access, ownership models, customer incentives and behavior of different bi-directional capabilities and service offerings. This will include determining how much and where to deploy V2X capable EVs and EVSE. The results of these activities could inform and support community based V2X projects.

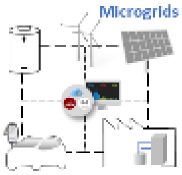
DOE could collaborate with NIST, Standards Setting Organizations (SSOs), and manufacturers to inform product certification standards that enable V2G interactions with the electric grid (e.g., UL certification), while ensuring consistency with other DER.

DOE could conduct a techno-economic analysis of AC and DC based V2X.

DOE could conduct education and outreach to educate state and local oversight bodies, consumers, building mangers, utilities, and other stakeholders about the potential cost benefits of V2X and various approaches to deployment. These stakeholders include community, transportation, and utility rate advocates.

vii. Smart Charge Management Techniques

The focus of this section is implementation of smart charge management. Figure II.23 illustrates the current situation from a research perspective, including example use cases for different vehicle charging scenarios and the associated challenges, needs and DOE initiatives underway in support of VGI and SCM. This section does not address applications of high-power charging (above 200 kW; the assumption is that EV drivers utilizing HPC want to be recharged as fast as possible and will not compromise their charge time in the interest of energy management. Strategic deployment of grid storage with HPC could present an opportunity to implement SCM to some degree at charging stations, but the benefits to EV drivers and station operators (beyond mitigating grid impacts or avoiding demand charges) have not been investigated.

	Smart Charge Management (SCM) Use Case Examples	Challenges/Barriers	Needs	DOE Initiatives
LDV[1]-Residential 	• Balanced/shifted loads to take advantage of utility programs (e.g., demand response) • Emergency power supply	• EVSE[2] incompatible with home Energy Management System (EMS) • V2X hardware availability	• Smart charging ecosystem (EV and EVSE) compatible with EMS • Open access EVSE/EMS with 'smart' protocols • Inexpensive V2X hardware	• Universal smart EVSE with SCM module • Open architecture EMS • Smart charge adaptor • Bi-directional charger
LDV-Workplace/MUDs 	• Balance workplace loads • Charge reservations w/optimized scheduling • Respond to grid conditions • Provide grid services[3]	• EVs w/o 'smart' protocols • Non-networked EVSE incompatible with EMS • Unpredictable EV availability and status • V2X hardware availability	• Smart charging ecosystem compatible with EMS • Reservation app for EVs and charger operators • EMS-grid interface for grid conditions/needs	• Universal smart EVSE • Open architecture EMS • Smart charge adaptor • AC/DC metering • Reservation system with EMS interface
MDV[1]- Fleets 	• Charge scheduling to support site operations and power limitations • Emergency ops (V2X[4]) • Utilization of mobile storage assets (e.g., V2X)	• EMS for fleet operations with connection to grid controlling entity (for grid conditions) • V2X hardware availability	• Smart charging ecosystem compatible with fleet management systems • Cost-effective V2X hardware	• Reservation system with fleet EMS interface • Open architecture EMS • Bi-directional chargers and DC-to-AC power inverters • DC metering
Microgrids 	• Manage grid resources and loads for autonomous ops • Provide grid services depending on energy availability	• Compatible connectivity and communication of all grid-connected devices • V2X hardware availability	• Open access common communication/control platform; compatible with multiple protocols; adapts control to microgrid and grid conditions	• Common Integration Platform (e.g., CIP.io at ANL Energy Plaza) with machine learning (ML) • Smart charge adaptor

[1] LDV=light-duty vehicles; MDV=medium-duty vehicles; MUD=multi-unit dwelling
[2] EVSE=Electric Vehicle Supply Equipment (i.e., charging stations)
[3] Grid services include demand response, demand charge mitigation, frequency regulation, charge capacity deferral, etc.
[4] V2X refers to power supplied from EV batteries to home, building or grid via bi-directional charger or DC-to-AC inverter

Figure II.48. Use cases for different vehicle charging scenarios and the associated challenges, needs, and DOE initiatives underway.

Since SCM is basically implementing a decision process to turn on, turn off or control the charge rate, a variety of use cases and control schemes are possible; the table presents some examples currently being addressed or considered. Common challenges to implementing SCM across vehicle charging scenarios result from the lack of "smart" communication capability in many EVs and the use of proprietary communication with EVSE and charging network providers. This limits the ability to integrate EVs or other grid-connected devices and modify the control scheme for individual EV owners, workplaces, or charging stations/plazas unless local control is an option within the proprietary network.

A prerequisite for SCM is the ability to exchange information regarding vehicle status, charging energy required and charging power available. This requires a "smart" standard protocol that enables two-way EV-EVSE communication to determine how much recharge energy the EV needs and how much charging power is available during the charge (i.e., dependent on the charging equipment and power available at the charging location). If SCM is to be employed across multiple charging networks, "open access" to EVSE is required to enable communication and control without the need for proprietary interfaces. An "open architecture energy management system (EMS)" enables open access via a common integration platform, i.e., a microprocessor-based controller that can communicate with EVSE and grid-connected devices, e.g., solar PV, building systems and energy storage, via standard non-proprietary protocols.

Smart use cases that depend on bi-directional power capability, such as EVs providing emergency power or grid services (i.e., V2X), require additional information about the conditions at the energy supplier interface (e.g., a building energy management system, premise meter, or distribution transformer) as well as additional hardware, such as bi-directional charging equipment or DC-to-AC power inverters, that meets power quality requirements of the building or grid.

SCM Implementation

Smart charge management requires connectivity and two-way communication between the vehicle, charging equipment and an energy management system or network operator. If SCM is to include grid level considerations, communication with a grid entity, e.g., the utility or DSO, is required as well. The telematic solution differs since vehicles do not communicate with local servers and the connectivity via aggregators or other networks to utilities/grid operators is evolving. Figure II.24 illustrates communication and control pathways that could be deployed as the population of electric vehicles increases and the business models for recharging mature. Additional pathways are possible, but these are adequate to illustrate connectivity and communication required for SCM.

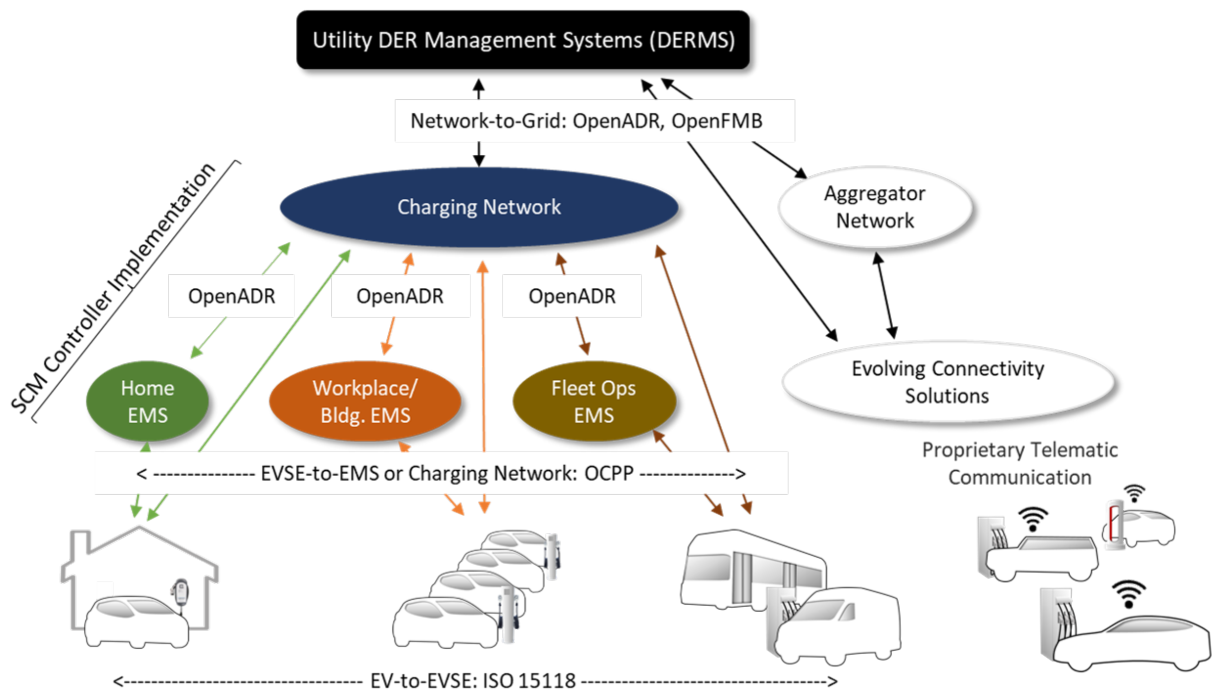


Figure II.49. Communication and control pathways.

The ISO 15118 protocol standard, which has been utilized in Europe and is being adopted by some U.S. vehicle OEMs, enables two-way communication, and provides the necessary vehicle information as well as other features to facilitate SCM at the local EMS and charging network levels (e.g., enables charge scheduling and real-time renegotiation to benefit EV drivers, station operators, and the controlling grid entity). The telematic pathway is notably different in that EVs do not communicate with grid operators via local energy management systems. SCM could be implemented at the OEM or aggregator levels in supervisory controllers that could communicate with an appropriate grid entity; or even direct communication with a grid operator is possible. Information to implement information could then be returned via the telematic links to the EVs to control the charge.

As mentioned previously, implementation of SCM at the next level of communication (i.e., EVSE-EMS/charging network) can be inhibited via the use of proprietary communication protocols. SCM can most readily be accomplished in a building/workplace EMS if EVSE are networked locally, they use a standard protocol (e.g., OCPP), and are not part of a commercial charging network. Otherwise, EVSE or the network provider must allow local control of the EVSE (via application programmer interface, or API) to participate in local energy management schemes. Though proprietary communication is an understandable element of a charging network's business model, it must be addressed if EVSE in the network are to be integrated in smart charging or building energy management systems.

Implementing SCM at the local level for vehicles using the telematic pathway is complicated somewhat by the indirect communication method between EVs and EVSE. SCM is being considered as an element of local control functions/grid services that include load balancing, demand response, frequency regulation, etc. Local control requirements to support some of these functions (e.g., response time, monitoring and control frequency) may not be compatible with the round-trip response time of telematic communication, but it will probably be manufacturer, make/model dependent and this has not yet been quantified.

DOE Research

The Vehicle Technologies Office (VTO) has several projects underway related to SCM, the two most prominent are Smart Electric Vehicle Charging for a Reliable and Resilient Grid (RECHARGE) led by NREL (Figure II.25) and Smart Vehicle-Grid Integration (Smart VGI) led by ANL. RECHARGE focuses on grid level analysis and smart charging strategies for EVs at scale while Smart VGI is focused on smart charge management on the customer side of the grid (See Section II.C.ii and II.C.iii).

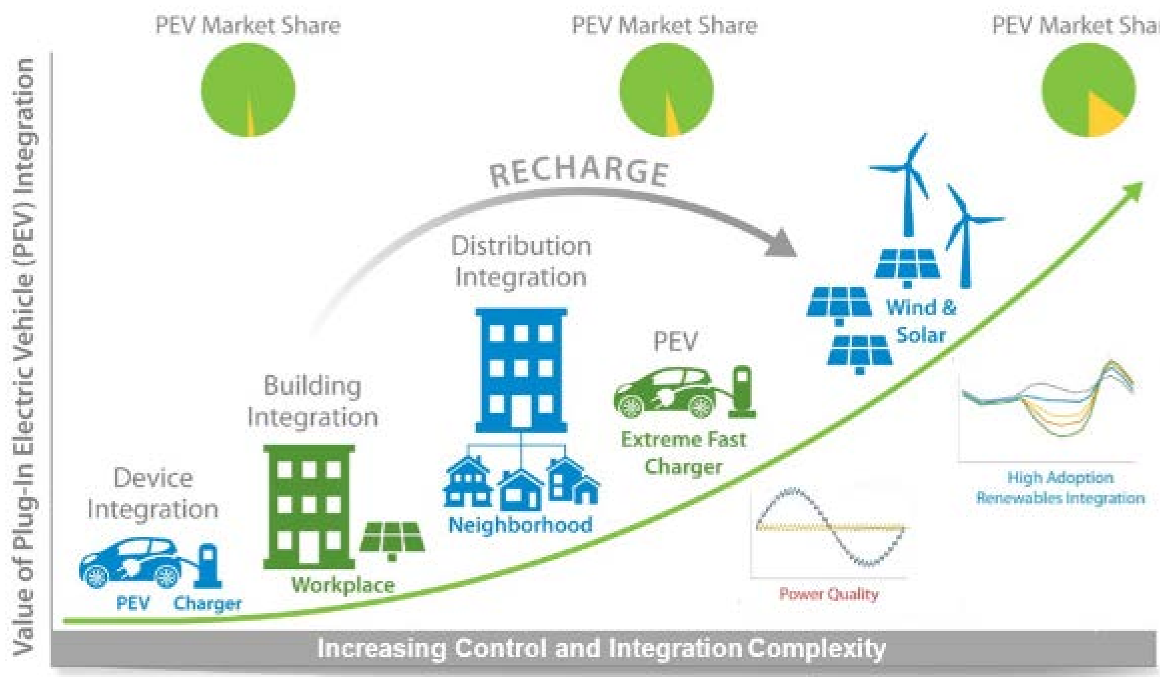


Figure II.50. NREL's RECHARGE project.

RECHARGE addresses the use and value of smart charge management to reduce the impact of EVs@Scale. The objective is to assess management of EV charging to avoid negative grid impacts, identify critical strategies and technologies, and enhance value for EV/EVSE/grid stakeholders[132].

- Estimate regional charging load
- Quantify the effects of uncontrolled charging
- Develop and evaluate the effectiveness of smart charge control strategies
- Identify required constraints and mechanisms to implement high-value charge control strategies

Smart VGI (Figure II.26) addresses barriers associated with connectivity and communication[133]. The objective is to demonstrate smart charging and energy management of a network of grid-connected devices as well as enabling technologies:

- Integrated communication and control of EVSE, building systems, solar PV, and energy storage with non-proprietary protocols and interfaces

[132] A. Meintz, Smart Electric Vehicle Charging for a Reliable and Resilient Grid (Recharge) (NREL), FY 2020 Electrification Annual Progress Report, U.S. DOE Vehicle Technologies Office, DOE/EE-2334, June 2021. pp. 536-547.[Online]:https://www1.eere.energy.gov/vehiclesandfuels/downloads/VTO_2020_APR_ELECTRIFICATION_COMPILED_REPORT_July%2014%20compliant_.pdf.

[133] K. Hardy, Smart Vehicle-Grid Integration (Argonne National Laboratory), FY 2020 Electrification Annual Progress Report, U.S. DOE Vehicle Technologies Office, DOE/EE-2334, June 2021. pp 465-472. [Online]: https://www1.eere.energy.gov/vehiclesandfuels/downloads/VTO_2020_APR_ELECTRIFICATION_COMPILED_REPORT_July%2014%20compliant_.pdf.

Support grid resiliency via dynamic response to grid conditions
Develop enabling technologies for metering, communication, control, and diagnostics

The project has demonstrated SCM utilizing the EV-EVSE-workplace EMS communication and control pathway with an open access smart charging ecosystem as well as the enabling technologies shown.

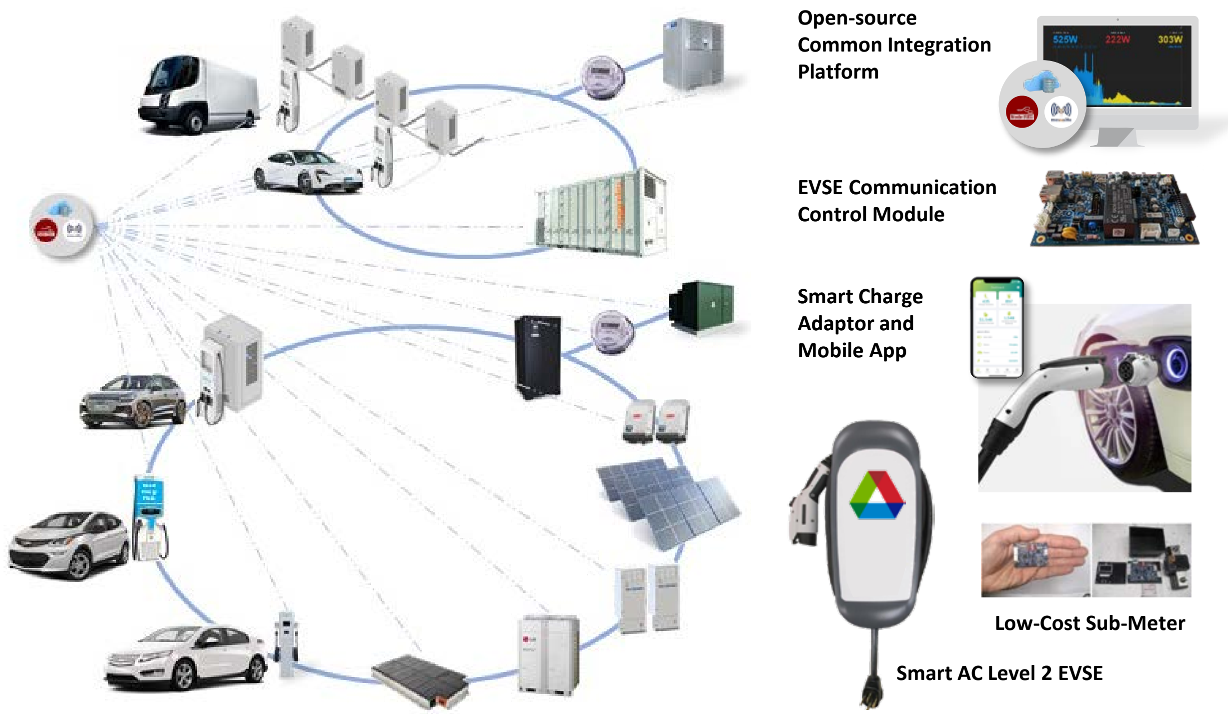


Figure II.51. Argonne's Smart VGI project.

Perspectives from SCM-related responses to DOE RFI

DOE's Office of Energy Efficiency and Renewable Energy (EERE) and Office of Electricity (OE) announced an RFI on electric vehicle grid integration on June 15, 2021, seeking feedback from industry, academia, research laboratories, government agencies, and other stakeholders on issues related to integrating EVs with the grid.

Reviewing the responses resulted in no surprises; the respondents deemed smart charging to be either a good idea or required to support the expected growth in EV sales and the associated demand for EV charging. This was qualified by comments that the benefit and value to stakeholders have not been quantified and further study was recommended.

The responses from technical organizations universally reinforced the dependency of smart charging on standard communication protocols and interoperability, though recommended implementation approaches differed, e.g.,

EV charging infrastructure should employ "open", non-proprietary communication standards

- EVs/EVSE should be treated the same as DERs, requiring the IEEE 1547 communication protocol
- EV-EVSE-grid operator communication pathways should utilize smart and open standard protocols, e.g., ISO 15118-OCPP-OpenADR/OpenFMB
- EVs should utilize a telematic communication pathway
- The market should decide on the pathways and protocols

Takeaways

- SCM can support a range of vehicle classes and charging scenarios to benefit EV users as well as the grid, but challenges to implementation include the lack of smart communication capability in many current EVs and the use of proprietary communication by EVSE manufacturers and charging network providers.
- Proprietary communication limits the ability to integrate EVs and EVSE in local energy management schemes to benefit individual EV owners, workplaces, or public charging stations/plazas. Though proprietary communication is an understandable element of a charging network's business model, it must be addressed if SCM is to be implemented locally (e.g., workplace or building energy management systems) or across multiple charging networks.
- Several different communication pathways and protocols are being considered to implement SCM for residential, workplace and fleet charging scenarios.
- DOE research is addressing challenges to SCM of LDVs, including projects focusing on grid level analysis and smart charging strategies for EVs at scale as well as development and demonstration of smart charging ecosystems and enabling technologies on the customer side of the grid. Several challenges remain to be addressed for commercial MDVs and HDVs with the potential to support SCM.
- Respondents to the DOE RFI on VGI supported SCM and reinforced the dependency on standard protocols and interoperability of EVs, EVSE and charging networks/grid operators.

Recommendations

- DOE could expand activities to develop and demonstrate VGI/SCM approaches to reduce grid impacts of on-road light-, medium-, and heavy-duty EV charging. SCM strategies that are vocation-specific could be considered, including control strategies requiring either temporal or locational charge flexibility to meet charging needs while mitigating grid impacts and providing value.
- DOE could develop and demonstrate smart charging ecosystem(s) to implement the SCM strategies consistent with utilities' operational environments, considering deployment within underserved and environmentally sensitive communities.
- DOE could expand activities to evaluate the round-trip response time and control frequency of the telematic communication pathway. The activity could determine the ability to support SCM and specific grid services at a local level, e.g., load-balancing, demand response or frequency regulation in a workplace environment. DOE could use resources

across national labs to provide technical assistance to utilities investigating implementation of SCM to integrate EVs with grid operations.

- Public funds expended for EVs and EVSE charging infrastructure could consider requiring smart communication capability and open access and/or local control options (i.e., non-proprietary communication) to ensure the opportunity to implement SCM programs. These requirements can be met with an open access charging ecosystem that utilizes standard smart protocols for EV-to-EVSE communication (e.g., ISO 15118-20) as well as open protocols for EVSE-to-energy management system communication (e.g., OCPP 2.0), EMS-to-charging network communication (e.g., OpenADR), and charging network-to-utility/grid operator communication (e.g., OpenADR or OpenFMB).
- Federally funded EVSE could be network agnostic to avoid stranded assets due to loss of a network provider for business or other reasons. Specifically, the EVSE could be owner-reconfigurable to communicate with a different server/network to maintain its availability and intended functionality to support SCM.

D. Codes and Standards

The successful wide-scale integration of EVs requires simplified, streamlined interaction across the EV ecosystem including robust, comprehensive standards and protocols for EVs, charging systems, and interconnection to the grid. Standards research, development, and demonstration is necessary to 1) enable smart charging for light-, medium-, and heavy-duty vehicles, 2) allow DER including EVs to perform grid services, 3) enhance local grid resilience, and 4) establish EV charging microgrids. Standards are required to enable networked communications and energy management systems to interface with multiple devices and communications protocols and for control strategies for charging equipment (individual or aggregated) to communicate with the grid. However, it is important to note that standards and protocols alone are not entirely sufficient as they do not cover the full end-to-end communication requirements. In short, advances in standards for communications, interconnection, and interoperability, as well as supporting test procedures and certification, are a necessity and will enable further work to harmonize requirements across technology domains, develop widely applicable interfaces, and promote seamless operation across the EV ecosystem.

Standards are not mandatory, but generally are in the form of baseline specifications according to which manufacturers can develop products with some increased assurance that they will interconnect and interoperate with those of other manufacturers, at least at a fundamental level. Standards serve to create the technical basis for a competitive market that offers buyers a choice of products, while supporting basic interconnectivity and interoperability. In the United States, standards development is an industry-driven consensus process. A protocol defines a set of rules used by two or more parties to interact between themselves. Specifically, with regards to electronic devices, a protocol defines how devices communicate with each other. These rules include what type of data may be transmitted, what commands are used to send and receive data, and how data transfers are confirmed. A code, as defined by Federal/state/local authorities and adopted by authorities having jurisdiction, is a set of mandatory technical specifications required for product implementation.

Key stakeholders with regards to codes and standards for the EV charging ecosystem include:

Standards Setting Organizations (SSOs): Society of Automotive Engineers (SAE), Institute of Electrical and Electronics Engineers (IEEE), American National Standards Institute (ANSI), National Electrical Manufacturers Association (NEMA), Underwriters Laboratories (UL), International Organization for Standardization (ISO), International Electrochemical Commission (IEC), German Institute for Standardization (DIN), and various alliances. SSOs include standards development organizations (SDOs) which are the organizations officially accredited to develop standards.

Research and Development Organizations: Automotive and truck OEMs, utilities, EVSE manufacturers, CNOs, and aggregators.

Testing and Certification Authorities: Underwriters Laboratories (UL), Intertek (ETL Mark), third-party testing under OSHA's Nationally Recognized Testing Laboratory (NRTL) Program, and CE MARK which affirms that products meet all the requirements of relevant European harmonized performance and safety standards.

Code Authorities: In the United States for codes, the National Fire Protection Association (NFPA) and relevant state and local code authorities.

This codes and standards section of the report examines five principal areas: codes and standards challenges; needs and opportunities; activities; drivers for communications and connectivity standards; and key takeaways and recommendations.

Challenges

The EV ecosystem is facing many challenges with regards to codes and standards (See Figure II.27). This includes the cross-sectoral and cross-functional nature of standards where standards connect multiple elements of the EV ecosystem (e.g., vehicle-charger, charger-charging network operator, and charging network operator-grid). Here, one standard often serves more than one function: for example, communications and cybersecurity or electrical requirements and safety. On the other hand, one standard cannot cover the full end-to-end communication pathway inherent to a V2X future (e.g., from EV through grid operator). Given the breadth of standards activity, another challenge is comprehensively understanding the current state of readiness, which is a prerequisite to identifying needs and requirements and establishing strategies for moving forward. Improvements are needed in the standards development processes themselves to better pace technology development throughout the EV ecosystem. Greater harmonization is also likely to be required especially with regards to U.S. and international standards. However, harmonization is a difficult goal and efforts are required to articulate its specific benefits and where it would be most appropriate and feasible.

Cross-Sectoral/Functional Nature of Standards: For the EV ecosystem, communications and connectivity are key and standards must consider the entire network including EVs, charging infrastructure, and the grid. Standardized communication methods are critical to implement smart charge management and vehicle-grid integration, which are critical enablers to further EV adoption. Smart charge management requires two-way communication between the vehicle, charging equipment, network operator, and the energy services providers – which in turn requires standardized connectivity (such as cellular or Wi-Fi), protocols (i.e., message format), and messaging (i.e., data model). The cross-sectoral nature of standards poses significant challenges, especially recognizing that standards are also cross-functional and inter-relational, not one dimensional nor isolated. A further challenge is the lack of clear delineation of the purviews and conflicting priorities of SSOs, especially between U.S. and international SDOs. Additionally, there is also lack of consensus amongst SDOs on preferred communication pathways and protocols, which is especially pressing given that standards development is often a competitive, commercial process. The use of communication pathways and protocols amongst EV manufacturers, charging equipment manufacturers, charging network providers, and utilities is also not uniform. Charging networks typically use a combination of standards and proprietary protocols, while vehicle and EVSE OEMs often use different standards by choice. Examples of protocols which are not universally accepted include IEEE 2030.5 (Smart Energy Profile), ISO 15118-2 (Open V2G), OPEN ADR 2.0-11 (Open Automated Demand Response), and OCPP.2.0 (Open Charge Point Protocol). Furthermore, discontinuities exist between vehicle OEM and power industry compliance and certification. For example, SAE standards maintain self-compliance while the power industry uses third-party standards compliance which makes integration between the two more difficult.

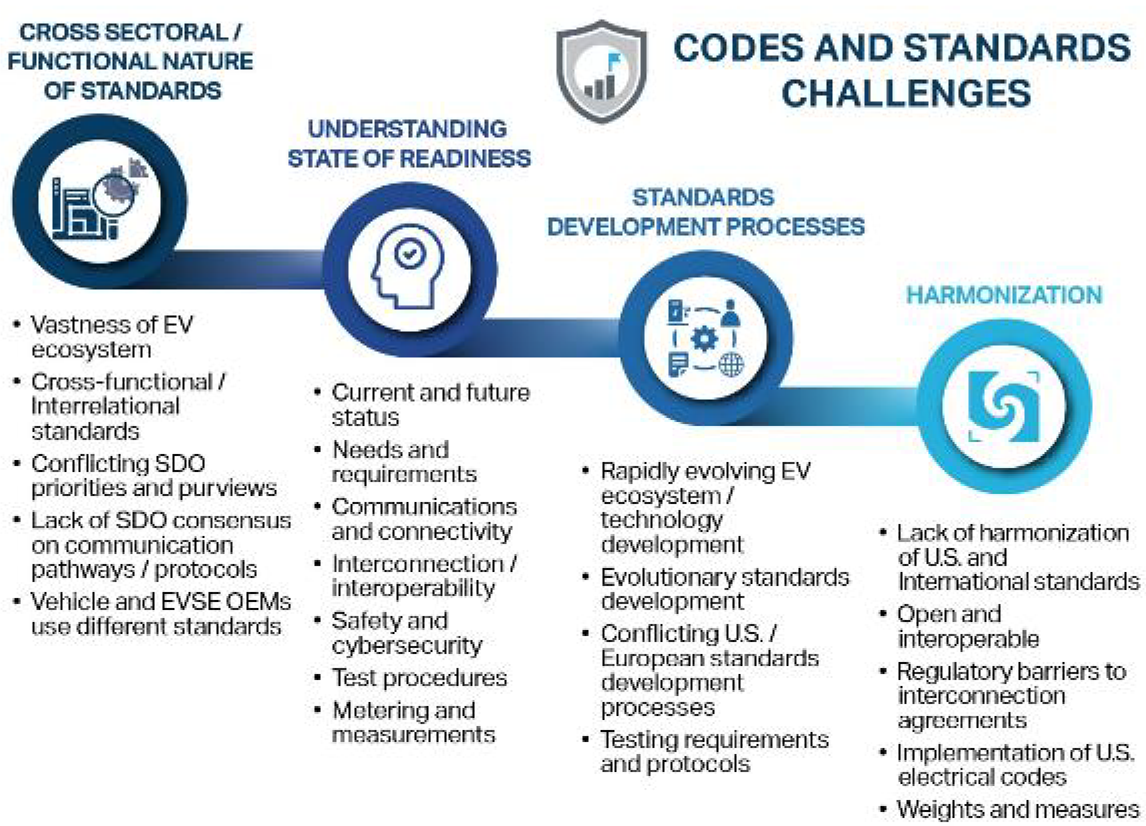


Figure II.52. Codes and Standards Challenges.

The aforementioned discussion shows that standards and communication protocols are not, in isolation, adequate to ensure interoperability between EV devices and systems. As such, the concept of an interoperability profile is important to ensure end-to-end interoperability for EV managed charging and V2X grid integration. Interoperability Profiles are developed based on requirements derived from specific use cases and describe the necessary elements from existing standards and communication protocols that can ensure interoperability and support the desired functionality. An example includes the NIST/Smart Energy Power Alliance (SEPA) interoperability profile for EV managed charging.[134]

Understanding State of Readiness: It is important to clearly identify the critical needs and requirements for codes and standards for the EV ecosystem. This includes standards essential for communications, connectivity, and safety and which incorporate robust interoperability and cybersecurity. Codes and standards and cybersecurity are closely interwoven and should be considered in unison. There are many challenges in this regard including better understanding which SSOs are responsible and accountable for particular aspects of the EV ecosystem, improved clarity of the smart charge management paradigm, and understanding the importance of cloud aggregators. It is also important to be cognizant of the state of development of test procedures in support of standards. Test procedures should be available when needed and must be accurate and represent reality. Test procedures must not overpredict the benefits of specific standards promising too much nor underpredict which would devalue potential standards benefits leading to little adoption. Metering and measurements are another important aspect of the EV ecosystem and must be kept in mind while keeping pace with standards requirements and technology development.

A key challenge facing codes and standards is the need to comprehensively assess the state of readiness of existing and future standards development activities. As an example of the complexity of this situation, the following Figure II.28 presents the interaction and integration of current SAE PEV communications, interoperability, and security standards documents. The solid lines and arrows represent first order, direct information exchange, while the dotted lines represent important, yet more secondary information flow. Here, depending upon specific use case requirements, different elements (represented by the / marking) of the SAE J2836 standard are being developed. For each use case, messaging/signaling requirements are being developed under the SAE standard J2847. Subsequently, these requirements feed into higher level standards requirements, including for power line communications (PLC), the Internet, and the local area network captured within J2931. J2953 captures overall interoperability requirements, and test plans, procedures, and metrics. The entire effort is wrapped in security requirements under J2931/7. In all, this involves the interaction of 23 SAE documents.

[134] Smart Electric Power Alliance Interoperability Task Force, EV Fleet Managed Charging Use Case, 2021, https://sepapower.org/resource/ev-fleet-managed-charging-use-case/

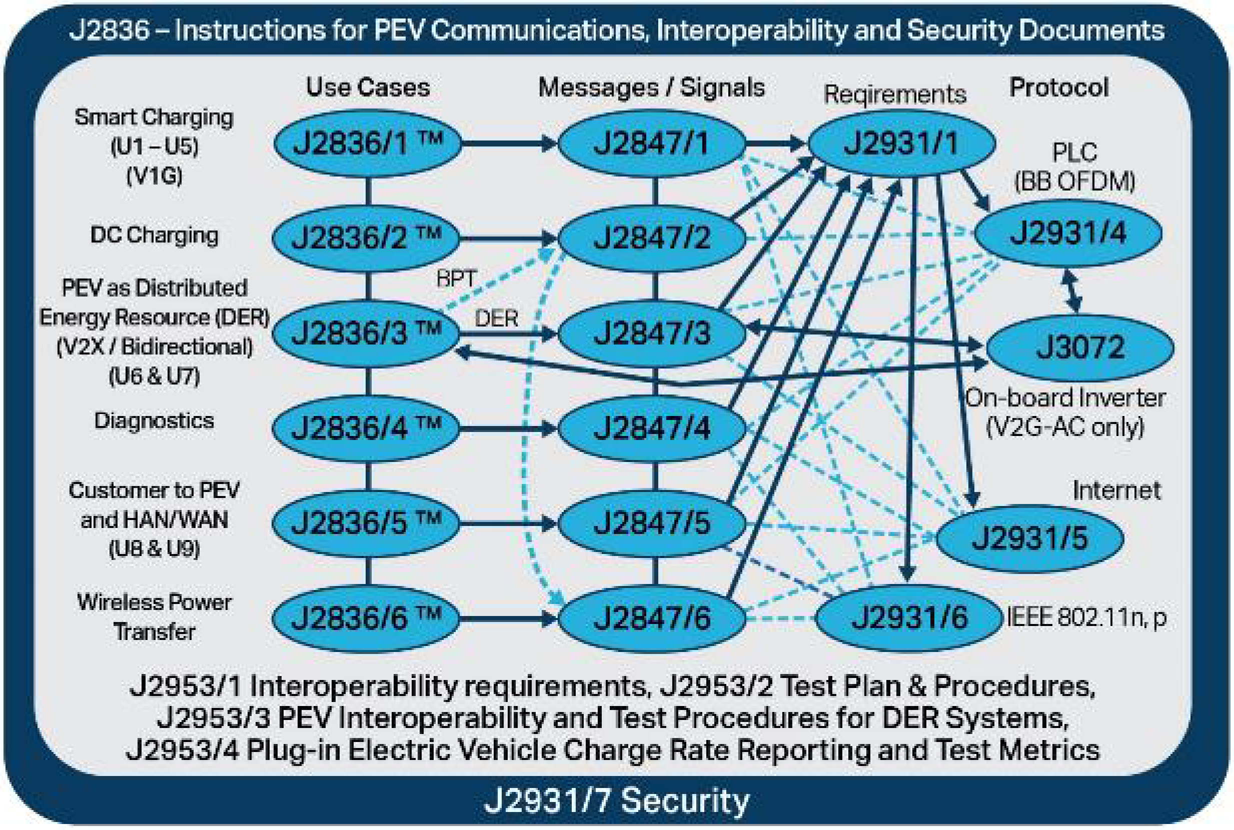


Figure II.53. Example of SAE Document Interaction[135].

Another area deserving of attention is commercial dispensing of electricity as a fuel. This is covered by State level weights and measures enforcement, with a +/-1% tolerance type approval certificate and billing information being required before an EVSE can be put into service. NIST Handbook 44-3.40 provides measurement requirements for commercial dispensing of electricity as fuel and is adopted by most states but enforced only in California as of January 2021. An Argonne National Laboratory benchmark study of NIST Handbook 44-3.40 suggests that acceptable DC EVSE meters are available for DC as a Service (DCaaS)/DER integrated charging, the Energy Services Interface (ESI), and P2030.13 systems. Presently, the biggest gaps with regards to commercial dispensing of electricity as a fuel include certification capabilities/locations where today there is only California Type Evaluation Program (CTEP) testing. There is currently no National Type Evaluation Program (NTEP) testing program for AC or DC EVSE. Additionally, county/local inspectors and Registered Service Agents (RSAs) need better test tools. Future requirements also include extension to other transportation sectors including mining, marine, electric vertical takeoff and landing (eVTOL), electric transport refrigeration units (ETRUs), and construction. The ANSI accuracy standard for DC metering (ANSI C12.32) was approved in 2021. The ANSI C12 meter specification series is typically used

[135] SAE Communication and Interoperability Task Force, April 12, 2021, Adaptation.

by PUCs/utilities as a benchmark for meter performance, including accuracy, while HB 44-3.40 addresses a dispensing system, not just a meter.

Standards Development Processes: Traditionally, standards development has been a process extending for many years and which can lag the quickly evolving pace of the EV ecosystem and integration of EVs with the grid. Figure II.29 generically outlines the basic structure of standards development which is different within the United States as opposed to internationally. The three fundamental pillars both for the United States and internationally are requirements for function, safety, and installation. Within the United States, each of these requirements are separate and distinct and led by different entities, be they SDOs, testing laboratories, or state and local authorities responsible for installation in accordance with state and local codes. Internationally, the two fundamental pillars of function and safety are intertwined, occur concurrently, and are led by ISO/IEC. Specifically, ISO handles communications, cybersecurity, and vehicle safety, while IEC is the lead for electrical requirements. Another difference is that U.S. standards documents do not always incorporate testing protocols, while ISO/IEC standards documents do. In Europe, where there is no equivalent to the UL, IEC writes documents that include safety requirements and products are self-certified. In the United States, the National Electric Code (NEC) generally requires products to be listed to UL standards based on third-party testing by Nationally Recognized Test Labs. With regards to installation, this is handled at the State level in the U.S. in accordance with state and local codes typically (though not always) following requirements of the NEC. However, state level building codes may be implemented using different versions of the NEC. Internationally, installation is managed through national standards.

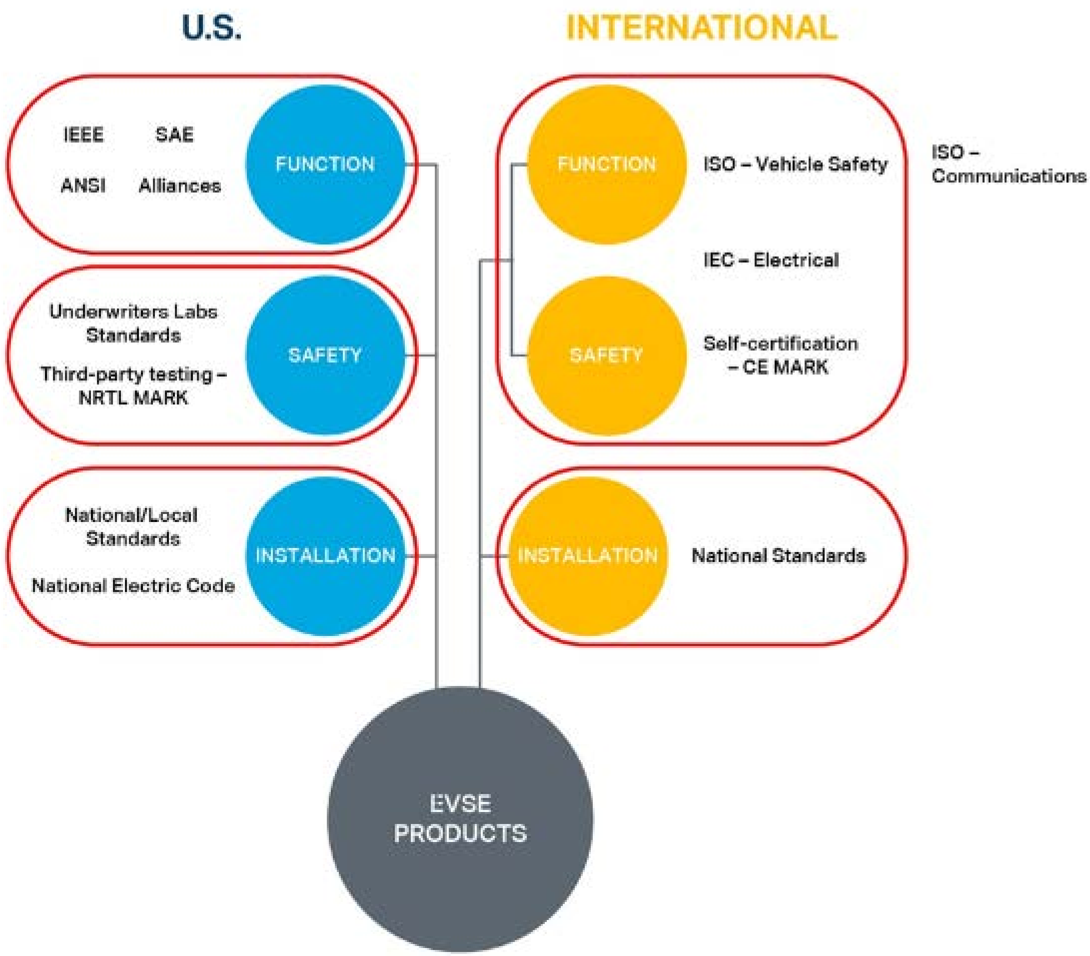


Figure II.54. Standards Development Structure: US and International[136].

For SAE, a three "stage" standards development process is typically followed including generation of an information report, recommended practice, and finally development of the full standard itself. The SAE process can be relatively nimble, allowing for production of a new document in as little as a few months. However, it can also be a process extending over many years (e.g., J1772 Combined Charging System and J2954 Wireless Power Transfer). Both ISO and IEC have a more rigorous fixed timeline process with multiple stages in production of a new document, generally taking several years to reach publication. This difference in "staging" and process is one factor that leads to incongruencies between U.S. and international standards development challenging efforts to coordinate and harmonize throughout the process. Within the United States, automakers are challenged to achieve alignment with non-automotive standards development practices. For example, NIST and NFPA traditionally update standards every 3 years. Automotive OEMs design products spanning much longer durations and a requirement for third-party certification to a non-automotive standard would be inconsistent

[136] EPRI Presentation "EV Charging Communications and V2G: SAE – ISO/IEC Comparison", Adaptation.

with the automotive certification process. Additionally, to support the standards development process itself necessitates the use of testing protocols and procedures which are often unique, scientifically challenging, and can require development of specialized technology. Furthermore, it is important to understand that standards are living documents, they can evolve and change a lot over time which necessitates diligence throughout this evolution process. It is not uncommon to see standards developed within some SDOs (such as IEEE, SAE, DIN, etc.), where the timeline to a published document can be much compressed, to later be adopted into ISO/IEC work.

Harmonization: Generically speaking, harmonization is the process of minimizing redundant or conflicting standards which may have evolved independently. A focus is to find commonalities, identify critical requirements that need to be retained, and provide common interoperable standards. For businesses, harmonization cuts compliance costs and simplifies the process of meeting requirements. It also reduces complexity for those tasked with testing and auditing standards compliance[137]. Harmonization is a process that can exist within standards development and potentially involves many nuances. For example, harmonization may involve alignment of key architectural concepts between standards. Typically, there are two tactics undertaken with regards to harmonization including moving to a single standard for a given application or maintaining multiple standards that are interoperable. For example, maintaining multiple standards is shown by the ability of a device to use Wi-Fi, Bluetooth, or cellular data to connect and interact seamlessly with the Internet. Harmonization may also exist within overall sets of objectives, such as part of broader efforts to create Interoperability Profiles such as being undertaken by NIST.

Standards development between SAE, IEC, and ISO are largely not harmonized for EV ecosystem communications and connectivity (see Figure II.30). Harmonization does exist between SAE J1772 and IEC 62196 and IEC 61851 for Level 1 and Level 2 AC charging for the charging coupler and basic electrical behavior between the EV and EVSE. But, for remote digital control of AC charging, which is required for smart charge management, harmonization does not exist between SAE and ISO standards. Harmonization does exist for the case of DC charging. As things get more complicated, specifically with regards to V2G, little harmonization exists. Harmonization does not exist for the AC vehicle to grid (Utility Interactive) scenario where the vehicle monitors voltage on the grid and injects power to the grid at a fixed power level and in phase. Here, international (ISO) standards do not follow IEEE grid codes used in the United States. Likewise, harmonization does not exist for the more advanced AC Vehicle to Grid (Grid Support Utility Interactive) scenario where the inverter does not necessarily follow the grid and the power output and phase angle may vary. This more intelligent system provides grid support based upon external communications and has flexibility to enable greater DER integration without disruption. For the DC Vehicle to Grid (Utility Interactive/Grid Support Utility Interactive) scenario, the power electronics that must interface with the grid are external to the vehicle, lessening the impact of the communications protocol used between the EV and EVSE. With regards to enabling Plug and Charge capabilities and ultimately harmonization, elements of the supporting ecosystem must be in place. At this time, existing SAE and ISO standards can

[137] Wikipedia, Standards Harmonization, June 14, 2021. https://en.wikipedia.org/wiki/Harmonization_(standards)

only partially support Plug and Charge until the rest of the ecosystem is established to enable this function, most notably that of a robust Public Key Infrastructure (PKI) which is not addressed in these standards. Efforts are in progress with regards to harmonizing SAE and ISO standards with regards to wireless charging control.

	SAE	Harmonized	IEC
AC Charging	Covered in J1772	YES	IEC 62196 IEC 61851

	SAE	Harmonized	ISO
Remote Digital Control of AC Charging	Supported with IEEE 2030.5 smart energy profile	NO	Supported as Payment (built into protocol)
DC Charging	Supported (built into protocol, based on DIN 70121)	YES	Supported (built into protocol, based on DIN 70121)
AC Vehicle to Grid (Utility Interactive)	Supported (J3072, IEEE1547-2013)	NO	Work in Progress (15118-20) (Not harmonized with US Standards)
AC Vehicle to Grid (Grid Support Utility Interactive)	Supported (J3072, J2847/3, IEEE1547-2018)	NO	Not Supported
DC Vehicle to Grid (Utility Interactive/Grid Support Utility Interactive)	Work in Progress[1] (IEEE 2030.5, UL9741)	N/A	Work in Progress (15118-20)[1] (Not harmonized with US Standards)
Plug and Charge	Can be Supported by IEEE 2030.5[2]	NO	Supported[2] (built into protocol)
Wireless Charging Control	Supported (J2847-6, J2836-6)	Work In Progress	Work in Progress (15118-20)

[1] EV-EVSE grid standards do not apply when exporting DC power

[2] Can only partially support Plug and Charge - requires whole ecosystem including PKI, which is not addressed in standards

Figure II.55. Harmonization of SAE Standards with IEC and ISO[138].

There are no ultimate showstoppers with regards to standards harmonization, but more a series of ongoing challenges and roadblocks. As mentioned in the previous section, U.S. standards documents do not always incorporate testing protocols, while ISO/IEC documents do. As a result, in the United States, UL standards must ordinarily be harmonized with SAE, as well as with ISO/IEC. To harmonize, this results in a lot of effort to achieve consensus with other entities as to the right type and amount of testing needed with regards to specific standards.

[138] EPRI Presentation "EV Charging Communications and V2G: SAE – ISO/IEC Comparison", Adaptation.

Additionally, on the U.S. side, UL standards can be trinational[139] with the United States, Canada, and Mexico. This requires coordination with these nations' working groups, overcoming conflicting interests, and ultimately achieving agreement when looking to harmonize with international standards. The NIST Standards Coordination Office works extensively with international SSOs on a variety of issues involving standards certification and harmonization.

Harmonization is also needed in other areas including utility interconnection agreements and at the state level with regards to Weights and Measures, the National Electric Code, and determining who has the right to sell electricity. Variations in utility structures and regulatory requirements mean that interconnection requirements with regards to V2G are very fragmented, in addition to V2G AC interconnection standards being nascent. Interconnection takes place at the local utility level and is typically governed by the state PUC or Public Services Commission. Another issue is harmonization of Weights and Measures at the state level. While guidance is provided at the Federal level (for example, through NIST documents/HB44-3.40), states are not required to adopt these recommendations for weights and measures. Furthermore, not all states follow up-to-date versions of the National Electrical Code, and some are even arbitrated at the local/county level. Finally, states have different requirements on which entities can own charging infrastructure and sell electricity as a transportation fuel within state boundaries.

Needs and Opportunities

As a result of the aforementioned challenges to codes and standards for the EV ecosystem, there are a number of needs that can be broadly categorized to include stakeholder engagement, coordination, and consensus; establishment of requirements; enhanced standards development processes; and implementation. Figure II.31 presents these broad needs and examples of specific elements within that are discussed in more detail in subsequent sections. Each area of need is followed by a short list of near-term, high-priority opportunities to further advance the development of codes and standards for the EV ecosystem.

Stakeholder Engagement/Coordination/Consensus: The need for strong, committed leadership and a clear vision is essential due to the vast, cross-sectoral nature of standards, especially recognizing that standards are also cross-functional and inter-relational. Strong, unified leadership would be enhanced by further development and maintenance of comprehensive public-private partnerships. The independent status and convening power of the government is useful to bring disparate codes and standards stakeholders together to reach a common vision and consensus on needs, stakeholder responsibilities, interoperability, and harmonization. A broad range of experience and a collective environment is highly beneficial to identifying challenges and reaching a unified vision and strategy. Current codes and standards development activities encompass a diversity of organizations and consortia from which it would be expeditious to leverage existing forums, processes, and mechanisms therein to achieve and implement a comprehensive standards

[139] Council for Harmonization of Electrotechnical Standards of the Nations in the Americas. [Online]: https://www.canena.org/

development strategy for the EV ecosystem. The following are two near-term priorities for stakeholder engagement, coordination, and consensus:

Unified Vision and Strategy: Convene forum of codes and standards stakeholders to jumpstart process to achieve a unified vision and strategy.

Stakeholder Workshop: Convene workshop with vehicle and EVSE OEMs, CNOs, utilities, and SSOs to clarify the potential of competing standards to support smart charge management and vehicle grid integration.

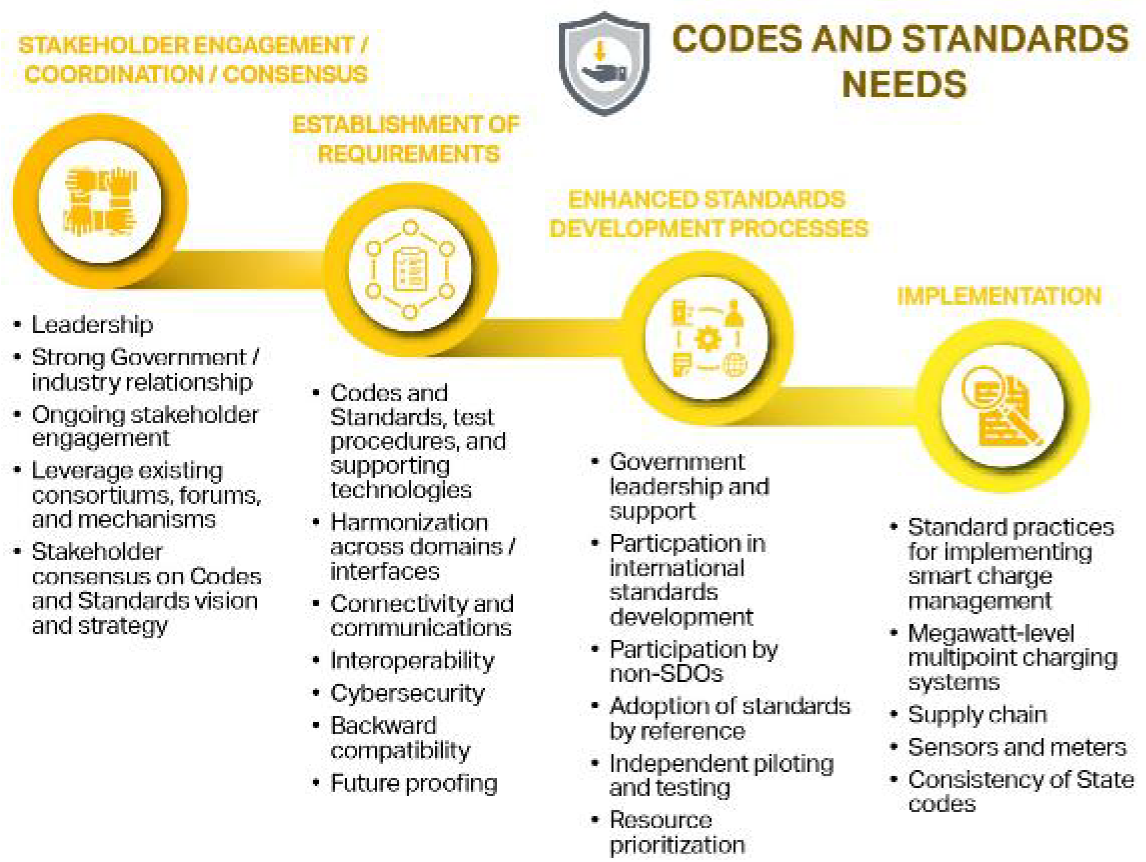


Figure II.56. Codes and Standards Needs

Establishment of Requirements: Subsequent to the development of a unified vision and strategy, a first order need is the establishment of high-level requirements for a broad range of codes and standards elements including communications, connectivity, interoperability, safety, cybersecurity, resiliency, backward compatibility, future proofing, over-the-air (OTA) updates, diagnostics, and metrics. Data driven, open, and functional standards with harmonization across domains and interfaces are important. For example, there are potential conflicts between electric grid focused communication protocols and EV-centric protocols. Here, interoperability must exist and if it does not barriers should be identified and fixed. A comprehensive review and assessment of the state of readiness of codes and standards, test procedures, and supporting technology requirements is essential. For example, standards really do not exist for the protection and safety of DC connected systems, for telematics, or for diagnostics or data reporting to identify issues that result in charging failures. Furthermore, network connected EV charging infrastructure should require capabilities for OTA updates. Consideration may also need to be given to how standards could extrapolate to rail, marine, and aircraft applications. The following are two near-term priorities for the establishment of requirements for codes and standards:

High-Level Requirements: In coordination with stakeholders, achieve consensus on high-level requirements for communications, connectivity, interoperability, cybersecurity, resiliency, safety, backward compatibility, future proofing, and metrics.

Standards Road mapping: Assess the status of codes and standards, test procedures, and supporting technology requirements; identify gaps; and determine priorities for moving forward.

Enhanced Standards Development Processes: Historically, the three key elements of the EV ecosystem– vehicles, charging infrastructure, and grid - have not been tightly coupled resulting in SDOs creating standards without interconnection and harmonization. It is also important to understand that the intent of standards is not to pick winners and losers and that standards development should not be overly prescriptive. There are several key elements that may serve to enhance the standards development processes including:

Government-industry leadership and coordination: It is important to establish a clear vision, obtain consensus, and achieve ongoing stakeholder engagement and support. More extensive government participation in existing forums would further this effort to achieve strong government-industry leadership and coordination.

U.S. Participation in International Standards Development: Given the international and inter- relational nature of standards and the need for harmonization, further U.S. Government coordination and engagement with international SDOs is needed.

Regulatory Issues: It is important to remain cognizant of potential regulatory issues, be it at the Federal or state level, which may impact or hinder resolution of technical issues with regards to codes and standards.

Participation of non-SDOs in the standards development process: Non-SDOs can be more flexible, move quicker, and can help serve the SDO process through framing of issues, establishment of needs and technical requirements, and testing and evaluation. Some examples include the SEPA, EPRI, and the Charging Interface Initiative (CharIN).

Adoption of standards by reference: This would allow standards to be developed and adopted much faster. For example, the Swift Charge (non-SDO) wireless standard could serve as a possible alternative to SAE J2954.

Independent Piloting and Testing: Early laboratory testing is essential to support the standards development process. ANL's PLC testing and NREL's testing events in support of the CharIN megawatt charging system (MCS) are prime examples. Interoperability testing is another key area of need. Government is well positioned to serve as an independent entity to provide unbiased review of assumptions, testing, validation, and resources to accelerate the standards development process.

Resource Prioritization: Given the scarcity of resource availability, including financial and workforce, diligent resource prioritization should be conducted to target the most critical needs and maximize the effectiveness of standards development activities.

The following identifies three near-term priorities to enable enhanced stakeholder development processes:

Government-Industry Leadership and Coordination: Expand government engagement with existing U.S. and international standards development organizations.

Non-SDOs in Standards Development Process: Expand participation of non-SDOs to enhance flexibility and expedite the standards development process.

Resource Prioritization: Based upon unified stakeholder consensus and strategy, prioritize financial and workforce resources to target the most critical needs.

Implementation: EVs should be able to plug in and charge anywhere, be interoperable, and at a minimum implement basic functionality. To support these requirements, implementation of codes and standards needs to be advanced for the EV ecosystem. For example, effective, widescale implementation of smart charge management requires establishment of uniform practices in coordination with supporting codes and standards. Furthermore, the challenges facing megawatt-level multiport charging facilities are extensive and currently not well understood. As shown in Figure II.32, uniform codes and standards are required to safely implement and operate megawatt-level multiport charging facilities. Codes and standards are required for each subsegment of the charging process. The supply chain is another critical area which has been underserved and requires increased attention from a codes and standards perspective, especially with regards to cybersecurity. The supply chain is especially challenging due to the large number and diversity of vendors; differing manufacturing, assembly, and management processes; and lack of comprehensive best practices and protocols. More consistency and harmonization of State codes would also be beneficial; for example, with regards to which entities can own charging facilities and sell electricity. Greater coordination across electrical and fire safety codes and standards is needed for the protection and safety of DC connected systems. The availability of a greater number of cheaper sensors and meters is also required to better gauge the effectiveness and benefits of the implementation of codes and standards and the EV ecosystem in general. The following are three near-term priorities for implementation of codes and standards:

Smart Charge Management: Identify actions to promote harmonization of vehicle-grid communications as an enabler for SCM and VGI. Promote standard industry practices for implementing SCM with local utilities.

Interoperability Testing: Further development of standards and test procedures for diagnostic interoperability testing for VGI, as well as less expensive field-testing equipment for AC and DC charging.

Energy Services Interface (ESI): Advance development of a standard energy services interface with an open, flexible format.

From Source to Load (grid-to-battery)

1) Utility Interconnection
2) AC/DC Power Conversion
3) DC Distribution, with DER Elements
4) DC Dispenser Electronics, Cables, Couplers, Micro-siting
5) Vehicle Inlet, Battery-BMS, Safety

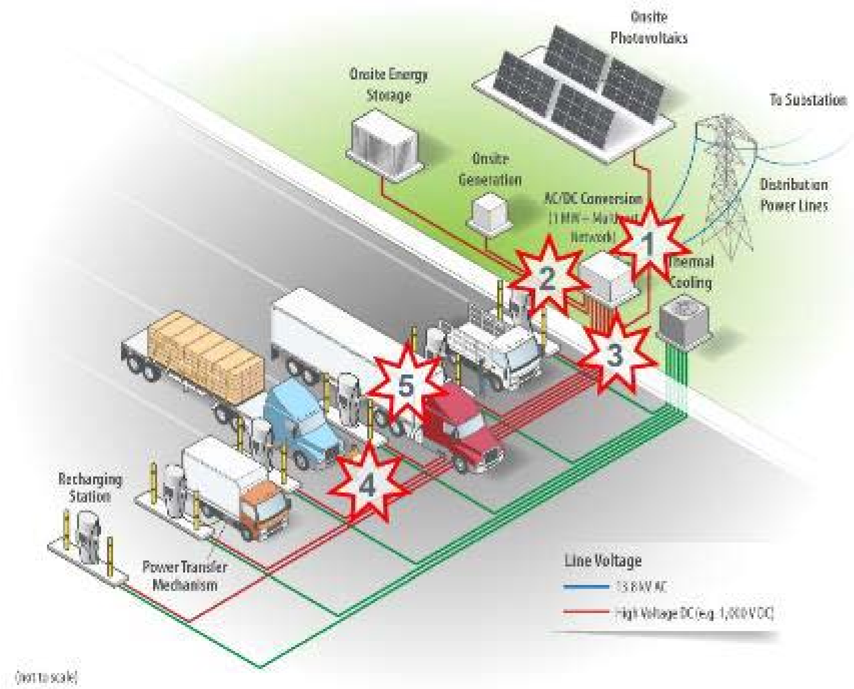


Figure II.57. MW+ Multi-Port EV Charging System (Standards are Applicable to each Subsegment of Process)[140].

Activities

The following section presents a synopsis of codes and standards activities by the DOE Grid and Infrastructure (G&I) Program, SDOs, non-SDO consortia and alliances, and codes bodies related to electric vehicles, charging infrastructure, and the electric grid. In recent years, codes and standards activities by the Federal Government have been of a relatively limited scope with activities being largely of a supportive nature. The G&I R&D Program within the DOE's VTO has continued codes and standards activities in several areas through the national laboratories. The G&I Program is working with SSOs, including SDOs, and is involved in many committee level activities. National laboratory representatives provide independent, unbiased, and highly skilled technical support to help identify R&D needs, challenges, and accelerate the adoption of standards. Specific technical activities include compact submeter and standards development and benchmarking of meters, current sensors, and secure gateway communications devices. The G&I program is collaborating with industry in developing and validating test procedures, identifying interoperability definitions, and the implementation of an ESI with industry partners via DCaaS activities. Additional standards related activities are the development of requirements and testing through CharIN for megawatt-level high-power charging couplers, including safety and communications testing for validation of interference to PLC signals during high power (3000 Amp) operation. In concert with wireless power transfer and vehicle OEMs,

[140] Source: National Renewable Energy Laboratory and Argonne National Laboratory.

efforts are exploring the potential to adopt-by-reference wireless power transfer requirements/ specifications to accelerate the development and implementation of standards. Finally, ongoing efforts provide contributions to and awareness of EV charging standards activities**.**

For a number of years, U.S. and international SDOs, non-SDO consortia and alliances, and codes bodies have undertaken codes and standards activities around electric vehicles, charging infrastructure, and the electric grid. Table II.3 presents many relevant codes and standards activities for these entities providing the organizational body, standard therein, a description of activities, and a link for further information. Officially, standards development organizations are the only entities which can develop and implement standards. However, non-SDO consortia and alliances can play a valuable role in facilitating the standards development process through the establishment of needs and requirements and conducting testing and evaluation which can expeditiously feed the standards development process. In the United States at the national level, the NFPA is responsible for development of codes related to electric vehicle charging. However, state and local code entities ultimately determine code requirements and subsequent implementation for electric vehicle charging infrastructure.

Drivers for Communications and Connectivity Standards

Grid (and vehicle) benefits can result from managing EV charging behavior (V1G) and/or leveraging the EV as a storage system (V2G) to enable better grid control. Standardizing communications and information models are a critical and rapidly evolving aspect of VGI. The speed at which industry understands, adopts, and utilizes good communication and connectivity standards can be a strongly enabling or potentially constraining factor to the pace of vehicle-grid-integration and EV adoption. Utility implementation of V1G and V2G will require the use of multiple communication protocols to satisfy the need for EV flexibility, with many choices existing for applications level communications (also referred to as messaging communications). However, the lack of industry agreement on preferred communications protocols for VGI offers no clear path and poses significant challenges moving forward. The following sections discuss major drivers and considerations impacting communications and connectivity standards for the EV ecosystem. This includes communications and connectivity protocols, the control architecture, charging connectors, conformance testing and certification, and electrical codes.

Communication and Connectivity Protocols define the format, meaning, and method of information exchange between devices or systems. Communication protocols can be proprietary, the exclusive property of an organization, or they can be open standards. Open standards are developed and maintained by standards development bodies for the benefit of all participants and are available for use by anyone. Open protocols enable competition between vendors, encourage innovation through openness, help to facilitate economies of scale as systems grow, and lower the costs of communications between different systems.

Table II.4 Codes and Standards Activities by Organization[141].

Standards Body	Standard	Description	Reference URL
American National Standards Institute (ANSI)	ANSI C12.32- DC meter standard	Develop OIML R46 compliant standard for DC meters to support Public Utility Commission (PUC) approved use for DC renewable/storage energy billing/credits	https://docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M345/K090/345090743.PDF
	ANSI US EV Standards Roadmap	Roadmap of all current US EV charging related standards and gaps (circa 2014 published; updated version discussed in context of global context)	https://www.ansi.org/news/standards-news/all-news/2013/05/updated-standardization-roadmap-for-us-electric-vehicle-deployment-released-14
Institute of Electrical and Electronic Engineers (IEEE)	IEEE 1547 Interconnection and Interoperability of Distributed Energy Resources with associated Electric Power Systems Interfaces	Covers control of grid tied electronics for DER and the latest versions include EVs as DER / storage assets	http://standards.ieee.org/standard/1547-2018.html
	IEEE P2030.13; Guide for Electric Transportation Fast Charging Station Management System Functional Specification	Direct application of DCaaS and other high power EV charging standards leveraging SAE, IEEE P2030.5 (SEP2), P2030.8 (AC microgrids), P2030.11 (DERMS). Standard launched in 2020.	https://standards.ieee.org/project/2030_13.html
	IEEE P2030.11; DERMS (Distributed Energy Resources Management Systems Functional Specification)	Guide for DERMS that facilitate aggregation and utility services. This serves both transmission and distribution levels.	https://standards.ieee.org/project/2030_11.html
	IEEE 2030.8; Standard for the Testing of Microgrid Controllers	Microgrids have specific needs on testing and implementation configuration validation, including storage elements and EVs. Published, used by other standards.	https://standards.ieee.org/standard/2030_8-2018.html

[141] Source: Argonne National Laboratory.

Standards Body	Standard	Description	Reference URL
	IEEE P2030.5; Standard for Smart Energy Profile Protocol	Leverages IEC (61968, 61850) standards. SAE J2836 and IEEE1547 are based on IEEE P2030.5. New profiles under development for EV charging for SEPA, Sunspec, SAE J3072 collaboration.	https://standards.ieee.org/project/2030_5.html
International Electrotechnical Commission (IEC)	IEC61980-1 Wireless power transfer	EV charging via wireless coupling; harmonized with SAE J2954	https://webstore.iec.ch/publication/31657
	IEC62196-3 DC EV charging cables/couplers	EV charging via wireless coupling; harmonized with SAE J1772 and CharIN MCS/IEC coupler stds. New IEC standard launched covering CharIN MCS.	https://webstore.iec.ch/publication/59654
International Organization for Standardization (ISO)	ISO15118 (parts 1-20) EV-EVSE communication	Plug-and-charge protocols; use cases and requirements for wireless communication; wireless power transfer; automatic connection devices and bidirectional power transfer; usage of private data; and cyber security.	https://www.iso.org/standard/69113.html
North American Energy Standards Board (NAESB)	Energy Services Interface (ESI)	National Labs working with NAESB and SEPA on standardizing ESI definitions, use cases, implementation via DCaaS.	https://www.naesb.org/
SAE International	SAE AE-7D AIR7357- MegaWatt and Extreme Fast Charging for Aircraft	Leverages CharIN MCS and other MW charging standards with DC storage/safety requirements	https://www.sae.org/standards/content/air7357/
	SAE J2953/1-2 AC charging interoperability	PEV Interoperability with EVSE. Stable usage. Leveraged in CharIN MCS and SAE J3105.	https://www.sae.org/standards/content/j2953/1/
	SAE J2953/3 DC charging interoperability	Test cases for PEV interoperability with EVSE. Stable, reflecting changes in SAE J2847/2, ISO 15118 related test cases, and tools.	https://www.sae.org/standards/content/j2953/3

Standards Body	Standard	Description	Reference URL
	SAE J2953/4 Plug-in Electric Vehicle (PEV) Charge Rate Reporting	Charging rate is dependent on the vehicle, EVSE limitations, and external conditions; standards. Definition and validation of test procedures.	https://www.sae.org/standards/content/j2953/4
	SAE J1772- EV and Plug in Hybrid Electric Vehicle Conductive Charge Coupler	AC and Combination AC/DC coupler (1000v/500A)	https://www.sae.org/standards/content/j1772_201710/
	SAE J3068- EV Power Transfer System Using a Three-Phase Capable Coupler	Three phase and DC multiple configuration coupler standard, up to 1000vdc/600vac using LIN bus digital communication and in the future differential CAN over cp-pp.	https://www.sae.org/standards/content/j3068_201804/
	SAE J3105 (part 1-3) EV Power Transfer System Using Conductive Automated Connection Devices	Overhead mechanized couplers for electric buses and port drayage vehicles; pantograph and motorized pin/sleeve types	https://www.sae.org/standards/content/j3105_202001/
	SAE J2954 (part 1-2) Wireless Power Transfer	Wireless charging for low power, high power in gap height of Z1-Z3, power class WPT1-WPT3 (3.3kW-11kW); WPT4-8 (22kW-500kW). Communication and alignment / association in progress.	https://www.sae.org/standards/content/j2954_201711/
	SAE J2931 (part 1-6) Digital Communications for Plug-in Electric Vehicles	Physical layer digital communication for EV charging including powerline carrier over pilot and wireless communication	https://www.sae.org/standards/content/j2931/1_201201/
	SAE J2931/7 Security for Plug-In Electric Vehicle Communications	Cyber security requirements	https://www.sae.org/standards/content/j2931/7_201802/
	SAE J1939 (parts 1-4) Vehicle CAN comm.	J1939-11 Physical layer definitions for vehicle CAN	https://www.sae.org/standardsdev/groundvehicle/j1939a.htm
	SAE J2894 Power Quality Requirements for Plug-In Electric Vehicle Chargers	Power quality and efficiency aspects of EV chargers	https://www.sae.org/standards/content/j2894/1_201901/

Standards Body	Standard	Description	Reference URL
	SAE J2997 Standards for Battery Secondary Use	Safety, BMS/state of health, liabilty issues	https://www.sae.org/standards/content/j2997/
	SAE J2836 (parts 0-6) PEV Communications, Interoperability and Security Use Case	Part 1-AC, Part 2-DC, Part 3-V2G, Part 4-Diagnostics, Part 5-Telematics, Part 6-WPT	https://www.sae.org/standards/content/j2836_201807/
	SAE J2847 (parts 1-6) PEV Communications Protocols	Part 1 SEP2/P2030.5 for AC charging, Part 2-DC, Part 3-V2G, Part 4-Diagnostics, Part 5-Telematics, Part 6-WPT	https://www.sae.org/standards/content/j2847/1_201908/
	SAE J3072 Interconnection Requirements for Onboard, Grid Support Inverter Systems	Based on IEEE 1547 and P2030.5 V2G standards. Supports AC and DC connected systems	https://www.sae.org/standards/content/j3072_202103/
Underwriters Laboratories (UL)	UL 1741 Inverters, Converters, Controllers, and Interconnection System Equipment for Use with Distributed Energy Resources	Covers photovoltaic inverters (possibly EVSE with power export)	https://standardscatalog.ul.com/ProductDetail.aspx?productid=UL1741
	UL 9741 Standard for Bi-directional Electric Vehicle (EV) Charge System, Edition 2, May 2021	This standard covers bi-directional EVSE that charge EVs from an electrical power system (EPS) and includes functionalities to export power from an EV to EPS.	https://standardscatalog.ul.com/ProductDetail.aspx?productid=UL9741

Standards Body	Standard	Description	Reference URL
Non-SDO Consortia/Alliances (leading to SDO adopted standards)			
CharIN	MegaWatt Charging System (MCS) for EVs	Industry led connector specification to be transferred to an SDO (SAE, IEC tentatively) for a 1500vdc, 3000A coupler. Subteam working on electrical safety requirements. Subteam working on physical layer communication test procedures and evaluation criteria while developing PLC alternatives. Coupler testing	https://www.charin.global/technology/mcs/

Standards Body	Standard	Description	Reference URL
Electric Power Research Institute (EPRI)	EPRI Infrastructure Working Group	Collaboration of Utilities, vehicle OEMs, EVSE manufacturers and other stakeholders on EV charging infrastructure, reflecting standards usage	https://www.epri.com/pages/sa/infrastructure-working-council
EMerge Alliance	DC Power applications industry consortium	Defacto standard on 380vdc building power systems and products, including DC microgrids, DC metering, controls (Enternet-Internet of power with communication)	https://www.emergealliance.org/emerge-alliance-committees/
ENERGY STAR (EPA)	ENERGY STAR EVSE (AC, DC) efficiency	Branding requirements, test procedures	https://www.energystar.gov/products/spec/electric_vehicle_supply_equipment_pd
International Organization of Legal Metrology (OIML)	OIML R46- AC, DC meter standards guidelines	International treaty on meter requirements. Harmonize with NIST HB44-3.40 EV charging transaction requirements.	https://www.oiml.org/en/files/pdf_r/r046-1-2-e12.pdf
National Conference on Weights and Measures (NCWM-NTEP)	Handbook 44-3.40, 5.55, NTEP Publication 14	NTEP Electric Vehicle Supply Equipment Work Group. Issues EVSE type approval certifications. States adopting HB44-3.40 for commercial dispensing of electricity as fuel.	https://www.ncwm.com/evse-wg
National Electrical Manufacturers Association (NEMA)	EVSE Task group of manufacturers	Work in parallel with NCWM, SAE on standards. Meter standards development that is adopted by ANSI (C12.20, C12.32)	https://www.nema.org/directory/products/view/electric-vehicle-supply-equipment-system
Open Charge Alliance (OCA)	Open Charge Point Protocol (OCPP)	OCPP V2X Task Group: focuses on the technical development of V2X use cases for the future versions of OCPP	https://www.openchargealliance.org/news/ocpp-certification-program-oca-is-looking-for-testing-laboratories/
Smart Energy Power Alliance (SEPA)	EV Charging and ESI working groups	White papers and presentations on managed charging	https://groups.sepapower.org/workinggroups/allworkinggroups/new-page
Sunspec Alliance	EV Charging, P2030.5 profiles, meter standards	MESA storage communication, PV, IEEE1547 compliance	http://sunspec.org/interoperability-specifications/

Standards Body	Standard	Description	Reference URL
Swift Charge Alliance	High power wireless charging consortium	Compatible but not interoperable with SAE J2954/IEC61980 WPT charging; able to reach higher power levels without exceeding ICNIRP/IEEE/EMC emissions limits (up to 1MW). Leverage SAE J1773/other inactive standards that could adopt by reference Swift Charge requirements/specs.	
U.S. Codes			
National Fire Protection Association (NFPA)	NFPA-70 Article 625	Definitions updated for new technologies (e.g., WPT). Eliminated "design requirements" with corresponding requirements in listing process. Allows liquid cooled EVSE cables listed by NRTL. Reverse power flow added to Code.	https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=70

For utility EV applications, protocols must be open and standards-based to accommodate the number and variety of charger vendors, EV manufacturers, and grid interfaces and systems. Interoperability standards, including open protocols, address the interfaces and communications between devices and systems, and the degree of interoperability is related to the maturity of the protocol and its ecosystem. Some protocols can support V1G, V2G, and a variety of other requirements for DER. However, while a protocol may be a good technical and business match for a specific application, it may not be for others. Given the nascent state of the managed charging and V2G markets, the landscape of protocol standards and technologies is evolving rapidly across multiple dimensions. As a result, while the value and need for standards is clear, the path to achieving widespread agreement is neither clear nor simple.[142]

The ***Control Architecture*** is another important consideration in identifying and specifying the required standardization of messaging protocols between the distribution utility, charging infrastructure, and EV. A control architecture describes the arrangement of elements and systems that enable communications between the grid operator and the end-device. Identifying the relevant stakeholders (otherwise known as actors) and understanding their needs will determine the communications architecture and communications requirements. Figure II.33 presents the four, primary grid to EV communications architectures of relevance to the EV ecosystem. Specifically, the figure shows how messages are exchanged between the controlling system via a utility DERMS, CNO, building EMS etc., and the charging systems or on-board EV control systems. Here, Pathway 1 uses a third-party aggregator to either “pass through” control messages and information or use the information to make decisions about charging behaviors of the managed EVs. Pathway 2 assumes some intelligent control system (e.g., a microgrid controller or a building energy management system) takes requests or commands from a utility DERMS and makes independent decisions how to use EV charging to meet grid requests. Pathway 3 leverages the CNO management of EV charging systems to meet grid requests or requirements. Pathway 4 is like Pathway 3 but uses the EV manufacturer’s telematics systems to communicate directly with the EVs, translating requests or mandates from the utility into specific EV charging/grid support behaviors. In all cases, the communications between the utility and the next point in the architecture is managed by the DERMS and the control architecture chosen impacts the communication protocol requirements and capabilities.[143]

[142] California Energy Commission, Staff Report, Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment – Analyzing Charger Needs to Support Zero Emission Vehicles in 2030, CEC-600-2021-001, January 2021. [Online]: https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127.

[143] California Energy Commission, Staff Report, Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment – Analyzing Charger Needs to Support Zero Emission Vehicles in 2030, CEC-600-2021-001, January 2021. [Online]: https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127.

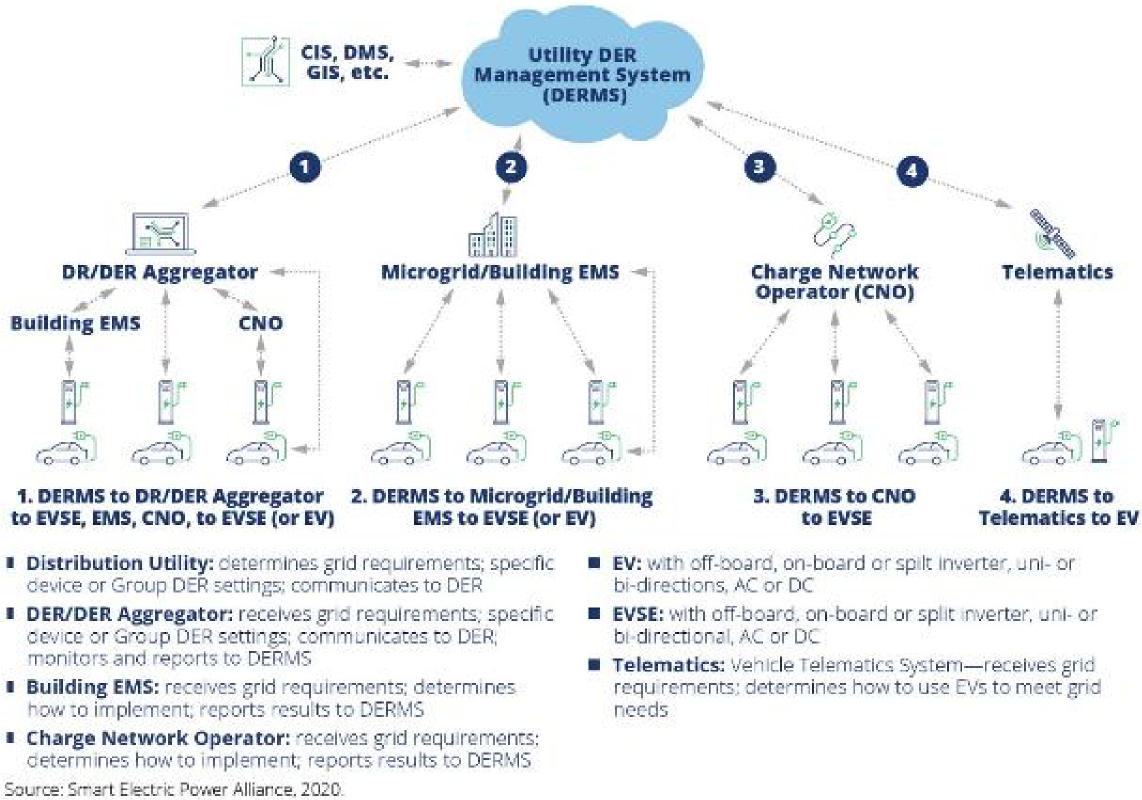


Figure II.58. Grid to EV Communications Architectures.

The landscape for communications protocols for EV management by grid operators is rapidly evolving. Some major open protocols of relevance include IEEE 2030.5 (Smart Energy Profile), ISO/IEC 15118 (also referred to as "OpenV2G"), Open Automated Demand Response (OpenADR), and the Open Charge Point Protocol (OCPP). For management of EV charging, Figure II.34 illustrates the communication segments that each protocol addresses. Many automakers and charging networks have publicly signaled their intention to adopt ISO 15118 as a more robust digital communications protocol between the vehicle and the charger. However, efforts to harmonize appear at a stalemate between proponents of ISO 15118 (American, European, and South Korean manufacturers) and IEEE 2030.5 (Smart Energy Profile) which is mainly supported by utilities in the United States. Here, there are technical differences between the standards that impact smart charge management and cybersecurity, and currently there is no apparent path to resolution. Each of the protocols continues to see increasing adoption and the SDOs and Interoperability Testing and Certification Authorities (ITCAs) continue to evolve the standards and certification programs. This rapid evolution makes protocol selection particularly challenging today and for the near future.[144] To reduce the interoperability issues in initiating charging sessions, the Federal Highway Administration has incorporated standardization based on ISO 15118 within the regulations for the National Electric

[144] California Energy Commission, Staff Report, Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment – Analyzing Charger Needs to Support Zero Emission Vehicles in 2030, CEC-600-2021-001, January 2021. [Online]: https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127

Vehicle Infrastructure (NEVI) Program effective March 30, 2023, with the intent to create a seamless driver experience across different models of EVSE and CNOs.[145].[146]

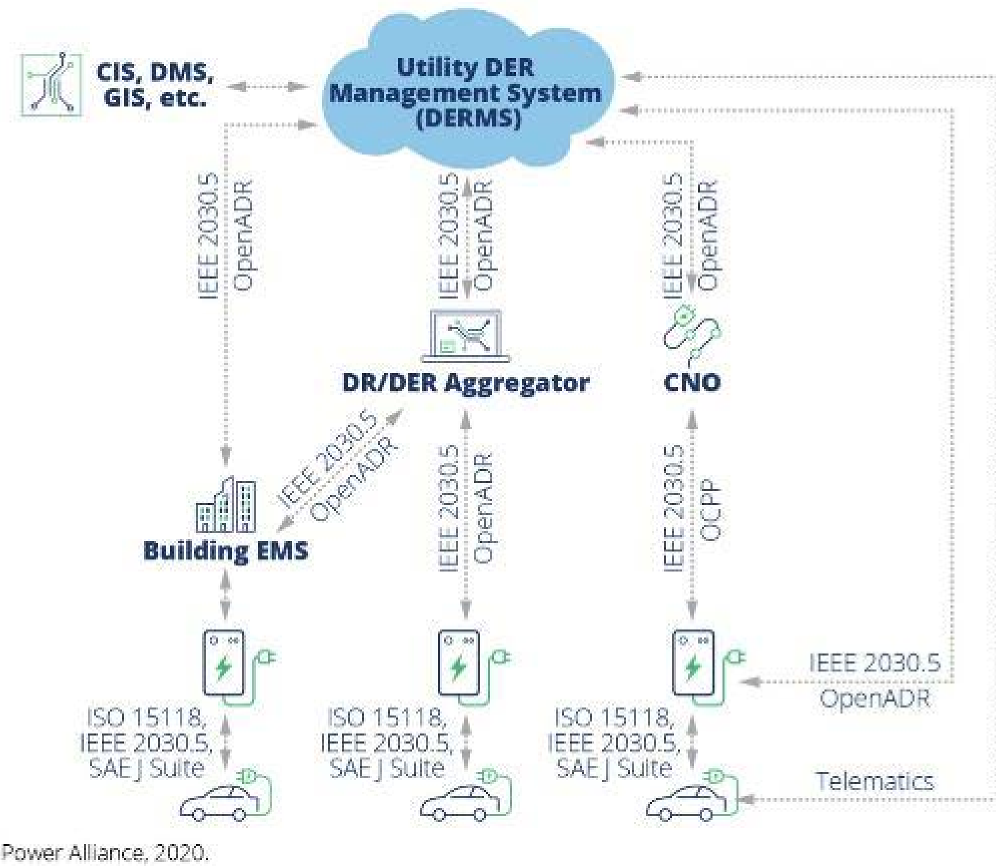


Figure II.59. Relationship between Key EV Communications Messaging Protocols.

Charging Connectors are another critical element of the EV charging equipment and provide the link between the charging equipment and the EV. However, despite years of market experimentation, charge connectors and communication protocols remain fragmented across many types of EVs. This lack of consistency needlessly inconveniences existing PEV drivers, feeds confusion among prospective EV buyers, and threatens to significantly hinder widespread vehicle-grid integration. DC fast charging connectors for passenger cars are split among three designs – Combined Charging System (CCS), CHAdeMO, and Tesla – even though all effectively serve the same purpose. The presence of multiple fast charging standards also increases the hardware complexity of charging stations and impedes greater use of EV charging. Fortunately, in North America, market players appear to be rapidly unifying around the CCS standard. The lack of connector standardization, however, is even more prevalent amongst medium- and

[145] Federal Highway Administration, 2022. National Electric Vehicle Infrastructure Formula Program Proposed Rulemaking FHWA-2022-0008. https://www.regulations.gov/document/FHWA-2022-0008-0001

[146] Federal Highway Administration, 2023. National Electric Vehicle Infrastructure Standards and Requirements Rulemaking FHWA-2023-03500. https://www.federalregister.gov/documents/2023/02/28/2023-03500/national-electric-vehicle-infrastructure-standards-and-requirements

heavy-duty EVs. The nascency of this market though may present opportunities to encourage standardization more aggressively in the relatively early stages. Still, many manufacturers of plug-in medium- and heavy-duty vehicles use proprietary connectors that are incompatible between different vehicles, and medium- and heavy-duty EVs are likely to use a wide array of charging interfaces (e.g., conductive connectors, automated pantograph, or wireless).

Figure II.35 presents the currently available and projected future charging connectors for light-, medium-, and heavy-duty applications; associated standards; max power levels; and typical applications within North America. Beyond the physical connector, the market has been slow to adopt standardized communication protocols between the vehicle and the charger, and between the charger and network.

Standards protocols are most useful when accompanied by **Conformance Testing and Certification** programs to help ensure vendors implement them uniformly. Without an effective certification program, vendors and users may choose incompatible combinations of features and capabilities from a protocol to support a specific application. System integration will then require significant interoperability testing, troubleshooting, and adjustments to be successful. Conformance testing and certification can eliminate these complexities by providing mechanisms to validate compliance with standards and that products provide the desired level of interoperability. Well-designed and executed certification programs are critical to ensuring that vendors implement the protocol consistently for the targeted applications. Some protocols already have robust certification processes in place to provide third-party validation, while others rely on self-certification and may or may not require the results to be reported. Utilities may want to perform their own spot testing or refer their service providers to known test tools and certification programs to increase the likelihood of interoperability. Each of these provide a different level of confidence in the accuracy of the results.[147]

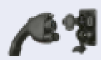
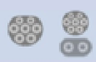
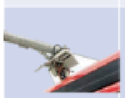
Diagram	Main Standard/ System	Maximum Output Power, Volts, Amps	Standard Status as of August 2023	Application Notes
	SAE J1772 / AC Level 1, AC Level 2	19.2 kW AC, 208/240VAC., 80A	Released	Used for Level 1 and Level 2 in North America. Commonly found on home, workplace, and public chargers.
	SAE J1772+ IEC 61851 / CCS1	450 kW DC, 1000VDC, 500A	Updating	Used for DC fast charging most vehicles in North America. Generally installed at public chargers.
	IEC 61851 IEEE 2030.1/ CHAdeMO	400 kW DC, 1000VDC, 400A	Released	Used for DC fast charging select vehicles in North America. Generally installed at public chargers.
	SAE J3400 / NACS	250 kW DC, 410VDC, 610A	In-development	Used for both AC and DC fast charging. Standard is under development and is based on Tesla's design.
	SAE J3068	166 kW AC, 600VAC, 160A 450 kW DC, 1000VDC, 450A	Updating	Standard for both AC and DC charging using the IEC 61851 'type 2' connector for North America three-phase charging.
	SAE J2954	22 kW AC light duty, 480VAC, 30A 500 kW AC heavy duty, 480VAC, 670A	Released	Wireless power transfer standard for MD/HD vehicles is J2954/2. In U.S. the maximum power for light-duty is 11KW (WPT3).
	SAE J3105	1.2 MW DC, 1000VDC, 1200A	Released	Automated connection device to charge MD/HD vehicles. Variants include pantograph up or down and pin-and-socket.
	IEC 61851 IEEE 2030.1 / Chaoji	900 kW DC, 1500VDC, 600A	In-development	Sub-MW conductive charging for LD/MD/HD vehicles in Asia
	SAE J3271 IEC 63379 / MCS	3.75 MW DC, 1500VDC, 3000A	In-development	Conductive MW level charging for MD/HD vehicles.

Figure II.60. Electric Vehicle Charging Connectors[148].

An **Electrical Code** is a set of regulations for the design and installation of electrical wiring with the intention to ensure electrical wiring systems that are safe for people and property. Such wiring is subject to rigorous safety standards for design and installation. Wires and electrical cables are specified according to the circuit operating voltage and electrical current capability, with further restrictions based upon environmental conditions, such as ambient temperature range, moisture levels, and exposure to sunlight and chemicals. To ensure both wiring and associated devices are designed, selected, and installed so that they are safe for use, they are subject to wiring safety codes or regulations, which vary by locality, country, or region. With regards to EV charging systems in the United States, the National Fire Protection Association-70

[147] Smart Electric Power Alliance, "Guidelines for Selecting a Communications Protocol for Vehicle-Grid Integration, August 2020. [Online]: https://sepapower.org/resource/guidelines-for-selecting-a-communications-protocol-for-vehicle-grid-integration/

[148] U.S. Department of Energy - Vehicle Technologies Office Electrification Program. *2022 Annual Progress Report*. Washington, DC: Vehicles Technologies Office, 2023. p.19, [Online]; Vehicle Technologies Office Electrification 2022 Annual Progress Report (energy.gov). Accessed 28 Nov. 2023.

(NFPA-70) NEC Article 625 is the relevant national code. However, the NEC is a regionally adaptable code and is not a Federal law. In some cases, the NEC is amended or altered and may even be rejected in lieu of regional regulations as voted upon by local governing bodies.[149]

Takeaways

- The EV ecosystem is facing many challenges with the cross-sectoral and cross-functional nature of standards where standards connect multiple elements of the EV ecosystem (e.g., vehicle-charger, charger-charging network operator, and charging network operator-grid).
- There is a lack of clear delineation of the purviews and conflicting priorities of SSOs, especially between U.S. and international SDOs.
- EVSE manufacturers, in particular, have a lack of clarity as to which standard they must comply with for their product which creates uncertainty.
- Comprehensive understanding the current state of readiness standards is required and is a prerequisite to identifying needs and requirements and establishing strategies moving forward.
- Improvements are needed in the standards development processes themselves to better pace technology development throughout the EV ecosystem.
- There is currently no NTEP testing program for AC or DC EVSE to certify measurement accuracy of electricity dispensed for retail charging.
- Greater harmonization is required especially with regards to U.S. and international standards. However, harmonization is a difficult goal and efforts are required to articulate its specific benefits and where it would be most appropriate and feasible.
- The automotive and electric grid standard environments operate on different time cycles and utilize different processes for certification which could result in persistent barriers.
- Most present-day EVs support over-the-air (OTA) updates to patch security gaps, add features / updates, and address reliability issues that are uncovered. New, network connected EV charging infrastructure deployment should include capabilities for OTA updates where available.

Recommendations

- DOE could expand activities to convene a forum of stakeholders to jumpstart a process to achieve a unified vision and strategy for codes and standards which identifies and addresses competing standards to remove barriers for smart charge management and vehicle grid-integration.
- Stakeholders, with expanded DOE support, could work to achieve consensus on high-level requirements for communications, connectivity, interoperability, cybersecurity, resiliency, safety, backward compatibility, future proofing, and metrics.

[149] Wikipedia, National Electric Code, June 8, 2021. [Online]: https://en.wikipedia.org/wiki/National_Electrical_Code

- DOE could expand activities to assess the status of codes and standards, test procedures, and supporting technology requirements; identify gaps; and determine priorities for moving forward.
- DOE could expand activities to strengthen engagement with existing U.S. and international standards development organizations to enable greater standards harmonization for EV-Grid integration.
- SDOs could expand participation by consortia of key stakeholders (SSOs such as CharIN) to enhance flexibility and expedite the standards development process.
- DOE could expand activities to support further development of standards and test procedures for diagnostic interoperability testing for VGI, as well as less expensive field-testing equipment for AC and DC charging.
- DOE could expand activities that, with stakeholder engagement, advance the development of a standard ESI with an open, flexible format.
- Stakeholders, with DOE support, could work to identify common diagnostics and data reporting approaches to identify interoperability, communications, or other charging failures proactively to simplify maintenance and improve up-time of EVSE.
- SDOs could, working with industry partners, require that deployment of new, network connected EV infrastructure have capabilities for over-the-air (OTA) updates where available to patch security gaps, add features/upgrades, and address reliability issues that are uncovered.

E. Cybersecurity

A lack of cybersecurity has the potential to be a major impediment to the large-scale adoption and integration of EVs with the grid. The vast cross-sectoral nature of the EV ecosystem, combined with the complexity of systems and technologies required to integrate EVs onto the grid, exposes a multitude of cybersecurity vulnerabilities. Apart from AC Level 1 chargers, EVSE has evolved rapidly to be networked and maintain a wide variety of communication functions. As communication networks for EVs, EVSE, and external systems increase, the attack surface also increases, leaving the charging infrastructure and wider EV ecosystem more open to exploitation of cybersecurity vulnerabilities. Cybersecurity breaches can affect the ability of charging equipment to function, expose personally identifiable and financial information, and more ominously affect safe operations of the charging equipment and the vehicles themselves, both during the charging processes and vehicle utilization.

A major challenge posed by compromised charging infrastructure is the threat it poses to the electric grid. A localized cyber-physical attack on a set of EVSE/charging stations can lead to a sudden addition or reduction of loads that can cause voltages imbalances and undesirable power quality impacts leading to local disruptions such as brownouts, market disruptions, and damaged equipment. Large-scale, coordinated cyber-physical attacks on charging infrastructure supporting large-scale EV implementation can also lead to wider grid disruptions, such as blackouts over large geographical areas. Finally, it is important to note that cybersecurity must be continually addressed as no EV ecosystem will ever be entirely secure and threats will continually evolve. The following sections examine cybersecurity challenges to the EV ecosystem; cybersecurity needs and opportunities; activities of the Federal Government and private sector to advance the overall cross-sectoral cybersecurity posture of the EV ecosystem; and key takeaways and recommendations.

Challenges

The EV ecosystem faces a significant number of daunting cybersecurity challenges (see Figure II.36). This includes securing a vast cross-sectoral multi-stakeholder ecosystem with the necessity to understand a myriad of cybersecurity threats and potential impacts. Significantly greater harmonization is required across many fronts and major advances are also required throughout the portfolio of systems, technology, and tool development to enable a holistic cybersecurity approach.

Securing a Vast Cross-Sectoral EV Ecosystem: Challenges to secure the vast cross-sectoral EV ecosystem (including EVs, charging infrastructure, and the grid) result from the multi-stakeholder environment, multiple sectoral interfaces, centers of control, and conflicting jurisdictional requirements and responsibilities. These factors blur lines of responsibility between stakeholders. Furthermore, there is an overall lack of inter-sectoral working experience, coordination, and trust amongst the EV ecosystem's stakeholders. Establishing and structuring trust is key in many areas including the PKI when providing system patching via

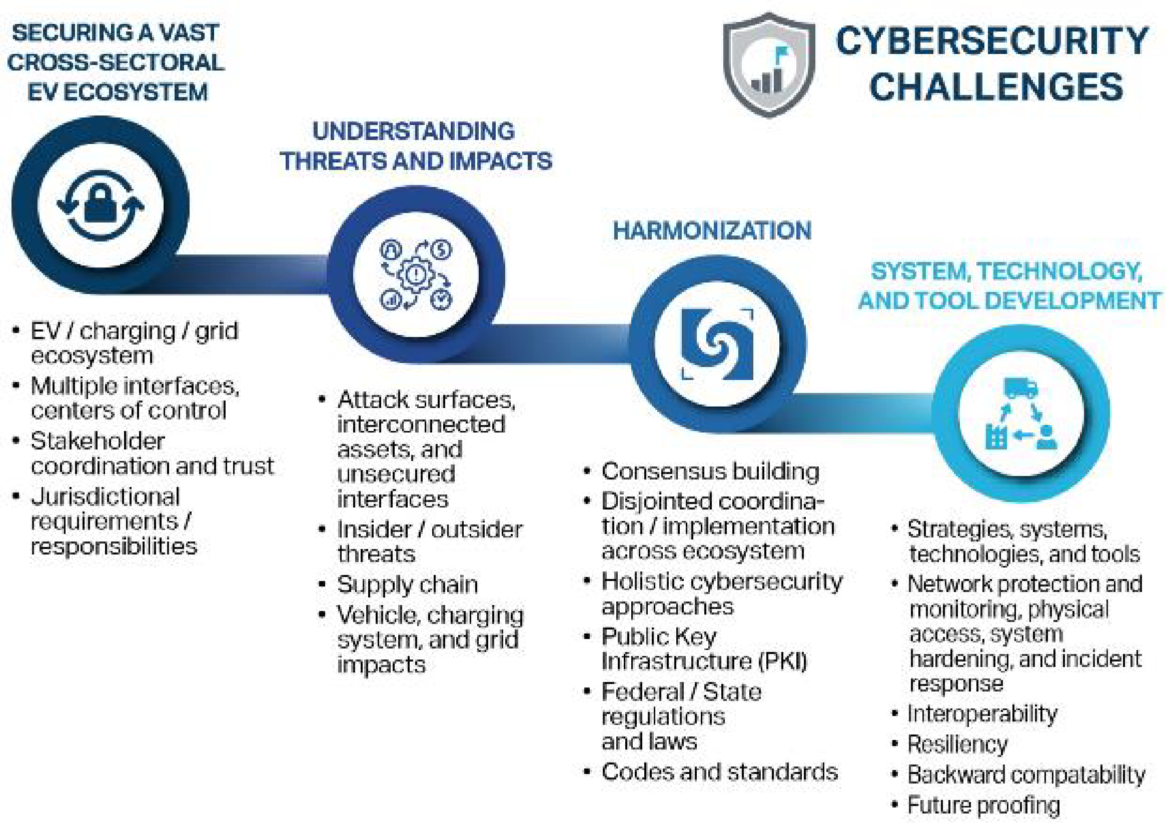


Figure II.61. Cybersecurity challenges.

over-the-air (OTA) updates, securing cloud services, achieving best-in-class network tools, as well as physical security. Trust is enhanced by greater user and information authentication through application of methodologies for data encryption, integrity, and secrecy, as well as more secure methodologies for command and control between stakeholders. Especially challenging are the interfaces and interconnections between each of the sectors and ecosystem components, and that cybersecurity for the EV ecosystem involves critical infrastructure and massive power devices. An additional barrier is that there are currently no specific guidelines for implementing EV charging cybersecurity.

Figure II.37 presents a communication architecture developed through industry engagement to identify the majority of specific communications standards, interconnections, control elements, and connections to the grid of an XFC infrastructure. Within the figure, the blue shading represents the charging facility itself, with on-site distributed energy resources (battery storage, onsite PV), control and conversion systems, communications, and extreme fast chargers. At the charge site, multiple entities and equipment are all communicating which need to be protected. In the upper left of the figure, important utility elements are shown including electricity transmission and distribution and associated control via the cloud. The balance of the figure largely presents various cloud services, including the vendor responsible for authorizing charging services and OEM communications with the electric vehicles. This figure helps illustrate the extent of the EV charging ecosystem that needs to be considered from a cybersecurity perspective.

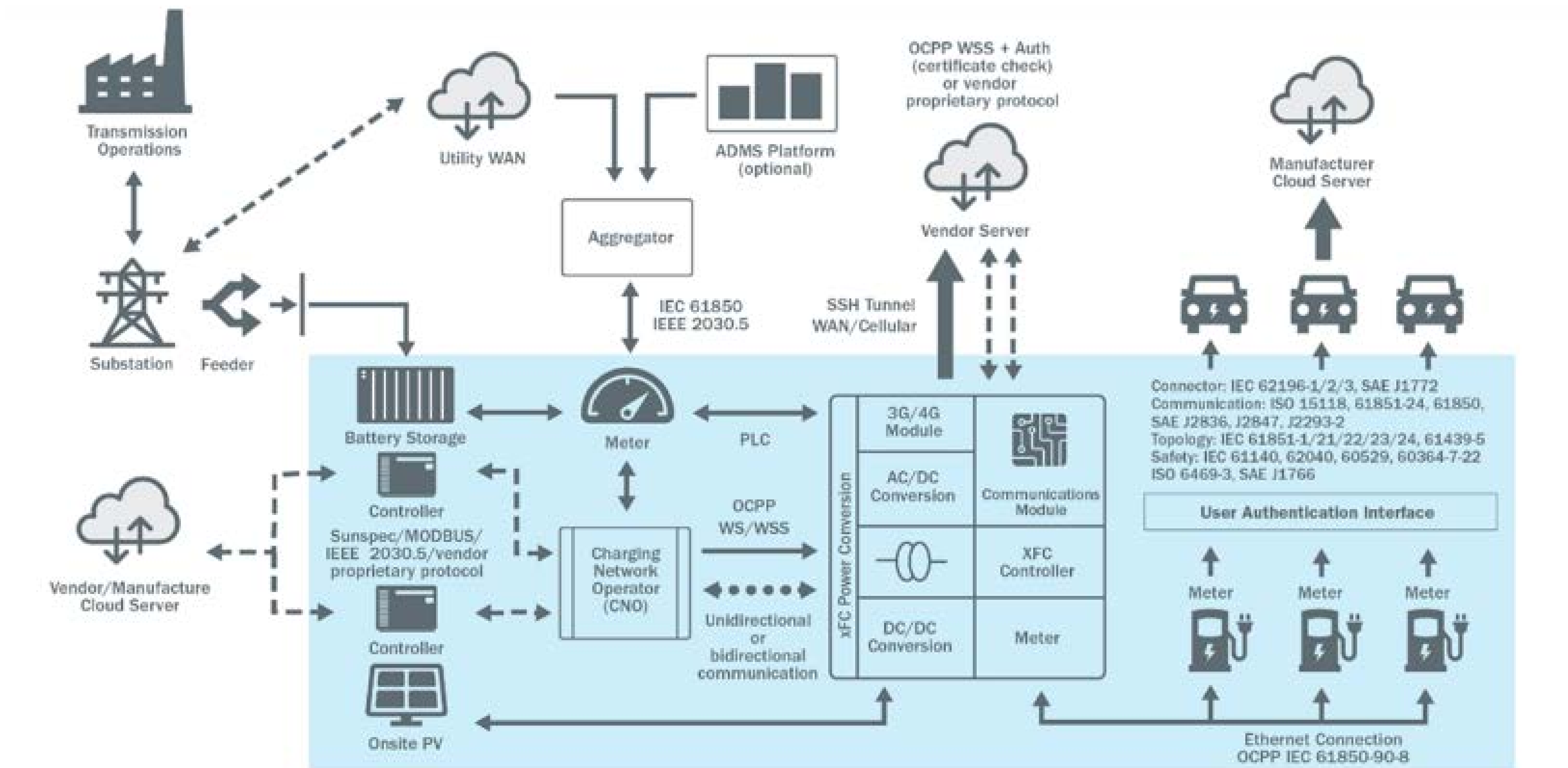


Figure II.62. Electric Vehicle Ecosystem Cyber Security Landscape[150].

[150] Consequence-Driven Cybersecurity for High Power EV Charging Infrastructure (Idaho National Lab, Oak Ridge National Lab, National Renewable Energy Lab), October 2020.

Understanding Threats and Impacts: The lack of a comprehensive understanding of cyber-physical security threats is a major barrier to the overall functionality, safety, and protection of EVs, charging infrastructure, and the grid. Specific challenges include incomplete industry understanding of attack surfaces, interconnected assets, and unsecured interfaces. An attack surface is a set of points, system elements, or endpoints whereby an attack could potentially breach, effect, or control systems and manipulate information. An unsecure interface is an unprotected or vulnerable shared boundary between system components where information is exchanged. To better understand the cybersecurity threat environment and conduct analyses, threat models are utilized. Figure II.38 presents a generic threat model of EV charging – grid impacts with an emphasis upon communication flows. The greyish box to the left presents key charging station elements, all synchronized by the EVSE controller. Above the station are important outside elements, particularly notable being the need for an established V2G root, a certificate authority to ensure the security of communications, and cloud services. On the right is depicted the communication pathways between the EVSE operator, EV service provider, and DSO of the energy distribution network, including relevant communication protocols therein. Threat models such as this help identify vulnerabilities, define security objectives, identify controls and mitigations to address threats, and identify potential consequences to the energy and transmission sectors. While considerable further understanding is needed of potential threats and impacts to the EV ecosystem, there are a number of already known potential issues[151].

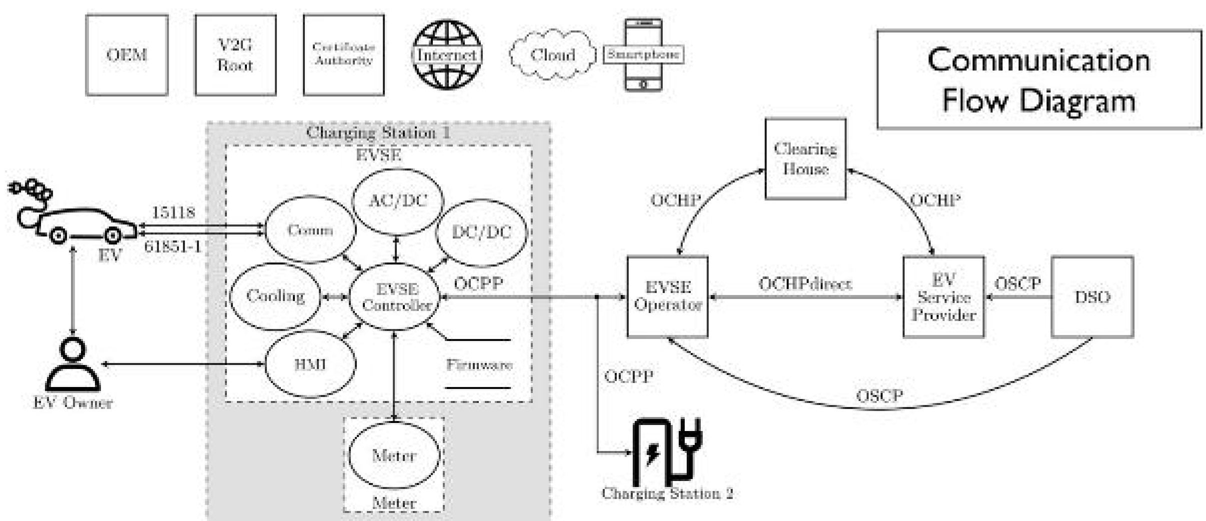


Figure II.63. Threat Model of EV Charging - Grid Impacts[152].

A fundamental challenge for the EV ecosystem is developing a comprehensive understanding of the potential resulting impacts locally and at a large-scale from cybersecurity breaches. Localized impacts include theft and/or illicit tracking of personal identifiable information (PII) and financial information, failure to charge vehicles, damage to batteries or other EV

[151] DOE/DHS/DOT Volpe Technical Meeting on Electric Vehicle and Charging Station Cybersecurity Report, DOT Volpe Center and DOE Office of Policy, Final Report, DOT-VNTSC-DOE-18-01, March 2018. [Online]: https://ntlrepository.blob.core.windows.net/lib/64000/64300/64315/EVC_Technical_Meeting_Report_190418.pdf
[152] Securing Vehicle Charging Infrastructure (Sandia National Laboratories), GITT Meeting, November 9, 2020.

components, and even compromise of EVSE and EV safety systems. Large-scale impacts include harvesting of PII and financial information, shut down of entire EVSE charging networks, exposure to upstream and partner IT networks, and misconfiguration of EVSE creating dangerous conditions. At the distribution system level, impacts include a sudden addition or reduction of loads that can cause local voltage imbalances and undesirable power impacts leading to brownouts and other disruptions. Large-scale, coordinated cyber-physical attacks on charging infrastructure can also lead to wide disruptions in electric grids and perhaps cascading failure type events causing blackouts to spread over large geographical areas. There are two main areas of concern in large-scale cyberattacks, that the attacker can “pivot” between components and networks to compromise information flows and/or the attacker can synchronize their attack to affect large portions of the grid simultaneously.

It is important to emphasize that not all cybersecurity threats emanate externally (whether from Nation states, organizations, or individuals), but also internally including disaffected employees with potential access throughout the ecosystem. Cybersecurity vulnerabilities along the entire length of the supply chain are also a major challenge including barriers arising from insecure design processes, requirements to minimize costs, the lack of codes and standards specific to the supply chain and limited best practices. Quantification of risks and development of actionable recommendations are needed to protect the charging infrastructure to enable vehicle transportation, charging, and utility stakeholders to better protect customers, vehicles, and power systems in the face of evolving threats.

Harmonization: To comprehensively address cybersecurity threats across the EV ecosystem and achieve harmonization, communication, coordination, and consensus must be achieved amongst key stakeholders. Greater harmonization will help define roles and responsibilities, reduce redundant research efforts, and increase stakeholder return on investment. Consensus building is a major challenge as every stakeholder has different interests, competitiveness strategies, and privacy and intellectual property concerns, all with a focus upon market position and the financial bottom line. The development of holistic, harmonized cybersecurity approaches amongst the stakeholders and across the interfaces are critical, as most current activities are largely disjointed across the EV, charging, and utility sectors. For example, disjointed coordination and implementation of standards and protocols (e.g., Open Charge Point Protocol 2.0) and technologies are major challenges, especially across the multitude of interfaces of the EV ecosystem. The establishment and acceptance of a universal PKI is a significant challenge and necessity. Another challenge is the lack of consistency and harmonization of federal, state, and local regulations and laws impacting cybersecurity, such as those governing acquisition of cybersecurity data and associated privacy. Finally, significantly greater cross-sectoral (energy and transportation) and international harmonization of the cybersecurity elements of codes and standards is a major challenge and ultimately an essential requirement.

System, Technology, and Tool Development: Research, development, and validation of systems, technologies, and tools are needed that identify, mitigate, and/or eliminate critical cybersecurity vulnerabilities resulting from EV charging and the need for increased levels of data sharing. Persistent weaknesses in EVSE systems requiring remediation include network monitoring and protection, physical access, and system hardening. Within the context to increase interconnection and interoperability of systems, both within sectors and across interfaces, cybersecurity for power flows and communications must be established and maintained. Developing resiliency for the entire system is essential, including perimeter defenses, intrusion detection and prevention, threat mitigation and isolation, and charging system recovery. Furthermore, development and implementation of cybersecurity systems, whether stand-alone or within the context of other systems or technologies, will require backward compatibility with existing legacy systems. Finally, a significant degree of future proofing will be required to allow systems to continually adapt to evolving threats and to accommodate implementation of newer cybersecurity technologies.

Needs and Opportunities

Cybersecurity needs can be broadly categorized to include stakeholder engagement, coordination, and consensus; gap analyses and needs assessments; research and development; and testing, validation, and demonstration. Figure II.39 presents these broad categories with examples of specific elements of interest therein.

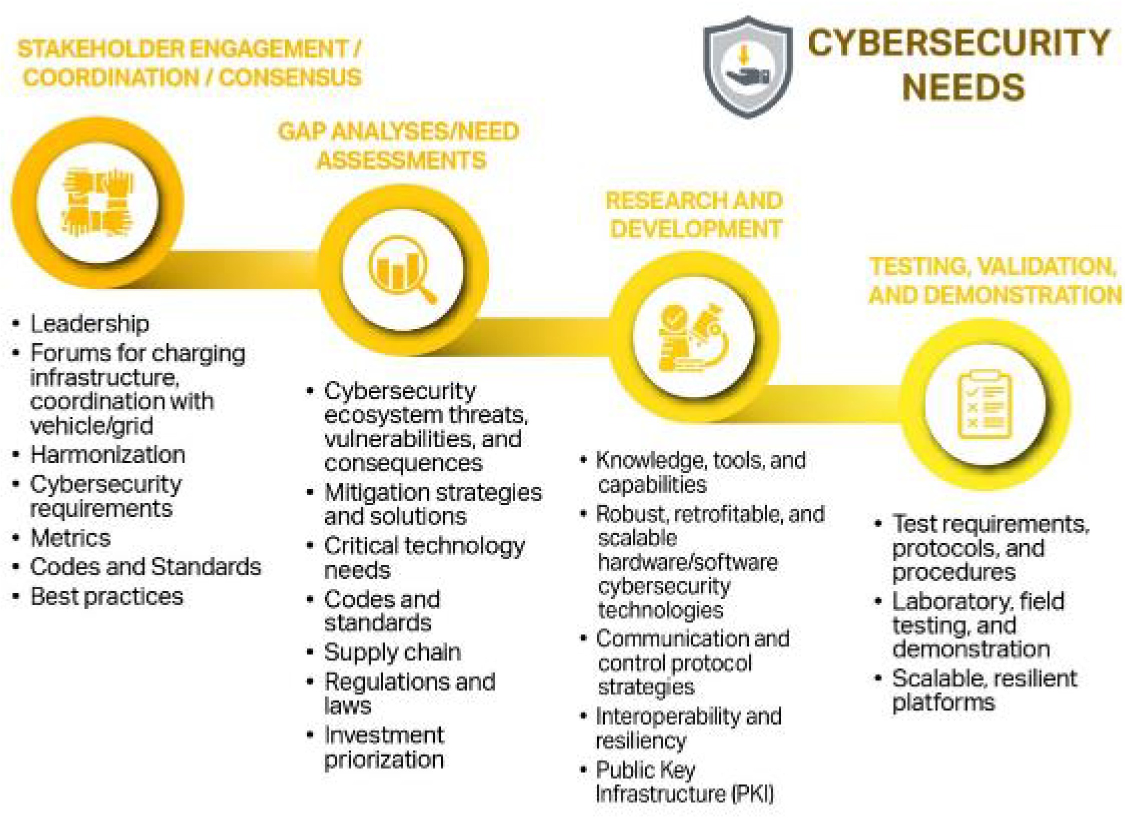


Figure II.64. Cybersecurity Needs.

Stakeholder Engagement, Coordination, and Consensus: As a result of the cross-sectoral nature of the EV ecosystem, strong stakeholder engagement, coordination, and consensus is essential to enable significant progress and establish leadership in securing the EV ecosystem. Neither well-established forums nor venues exist for discussing and resolving issues with regards to cybersecurity and charging infrastructure, including coordination with vehicles and the grid. Consensus building and harmonization is a significant problem, whether for establishing cybersecurity requirements or harmonizing across sectors. Cyber resilient design metrics and principles are needed that consider large scale EV penetration. Specifically, stakeholder engagement and consensus are needed to develop widely accepted cybersecurity metrics (including survivability, recovery time, resilience, etc.) and threat mitigation for numerous applications including high-power charging stations and EV smart charge management across networked, grid connected systems. Furthermore, extensive, sustained coordination and consensus is required to advance codes and standards especially with the understanding that numerous standards development organizations (e.g., SAE, IEEE, ISO, IEC, and ANSI) are highly active and relevant within this space, but do not always have a clear delineation of purviews and responsibilities. Additionally, best practices are needed for business networks and operations, EVSE security, EVSE networks, and EVSE operations. The following are five near-term priorities for stakeholder engagement, coordination, and consensus:

- Leadership: Establish cybersecurity leadership for the EV ecosystem based upon comprehensive input and consensus from key stakeholders.
- Cybersecurity forums for the EV ecosystem: Establish high-level forums, venues, working groups, and mechanisms to identify and address key cybersecurity challenges.
- NIST Cybersecurity Framework: Leverage the NIST Cybersecurity Framework to help bound and guide the structure of future cybersecurity strategies, approaches, and activities.
- System and technology approach: With stakeholder consensus, establish broad parameters for a comprehensive system and technology approach, including codes and standards.
- Cybersecurity Education and Workforce Development: Work with stakeholders to accelerate the development of the cybersecurity workforce. Examples include participation in student competitions such as the Cyber Auto and Cyber Truck Challenges.

Gap Analyses and Need Assessments: A comprehensive assessment and understanding of the risk landscape is required to lay a foundation for securing critical infrastructure. This includes cybersecurity ecosystem threats, vulnerabilities, and consequences, including the identification and prioritization of high consequence events and mitigation strategies. A thorough understanding is needed of attack surfaces, interconnected assets, and unsecured interfaces, as well as identification and prioritization of high priority strategies and critical technology needs. Once established, broad awareness is needed across key stakeholders within the EV-Grid ecosystem. Figure II.40 presents a block diagram of the approach to assessing the risk and consequences to the EV ecosystem. In short, two largely parallel activities are conducted including vulnerability assessment and threat model development, and investigation of consequences associated with charging and vehicle vulnerabilities, with a special emphasis upon the grid. These efforts ultimately culminate with the development of a comprehensive risk matrix and prioritization of mitigation strategies.

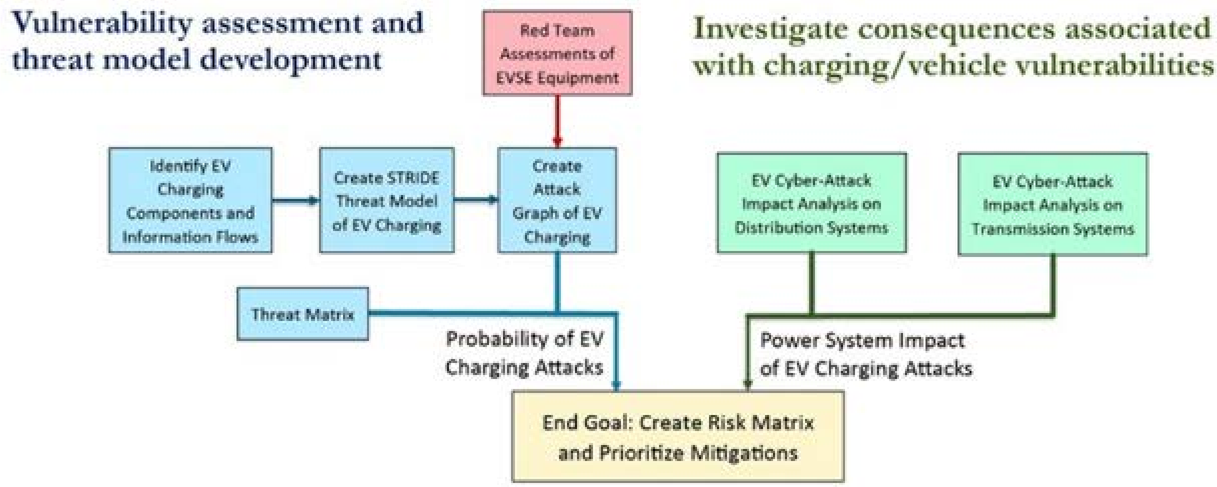


Figure II.65. Block Diagram of the Approach to Assessing the Risk Landscape of the EV Ecosystem[153].

Vulnerability assessment is an evaluation process used to rank cybersecurity weaknesses in order of importance or risk. Figure II.41 provides more details with regards to the process steps undertaken by Idaho National Laboratory (INL) when assessing vulnerabilities of electric vehicle supply equipment. This includes identifying attack pathways and vulnerabilities therein, and subsequently attempting to find means to compromise the system. Figure II.41 also presents a diagram of the communications network used at INL for cyber research. Here, two EVSE (50kW DC fast charger and 350kW XFC) are connected via a local management network to systems simulating communication protocols (i.e., OCPP and OpenADR) and a local energy aggregator (which simulates distributed energy resources such as solar and battery energy storage). In addition, the 350 kW XFC is connected to a grid emulator representing the utility power supply.

[153] Securing Vehicle Charging Infrastructure (Sandia National Laboratories), GITT Meeting, November 9, 2020.

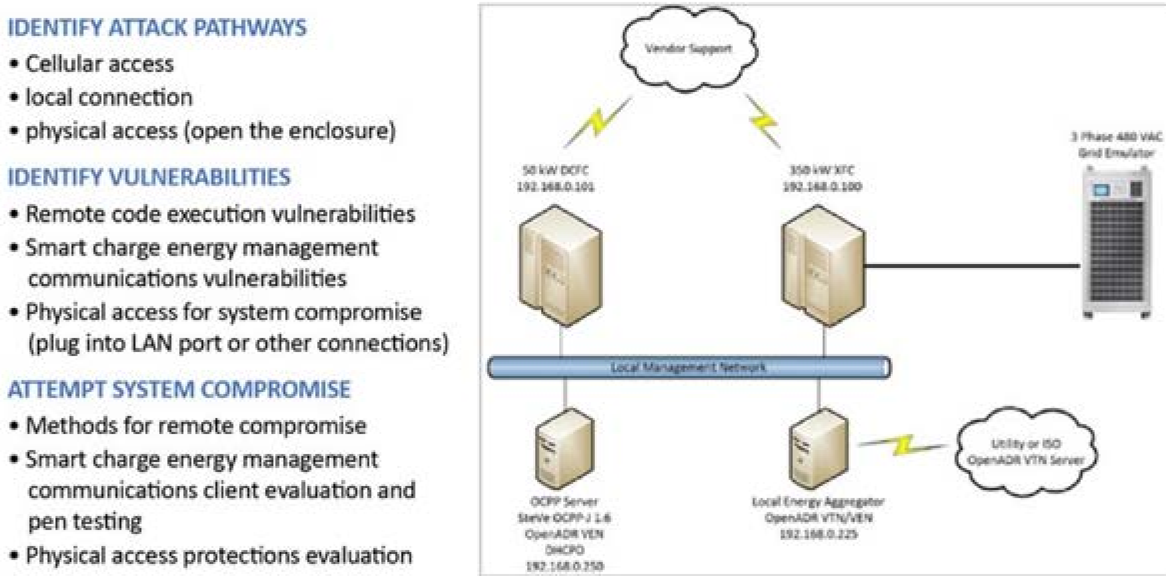


Figure II.66. Process for Vulnerability Assessment and Diagram of Communications Network used at INL for Cyber Research.

Codes and standards, the supply chain, and regulations and laws are also essential elements of robust cybersecurity. Codes and standards (including international) must be harmonized for cyber-physical security, including interconnection, interoperability, and test procedures. Presently, cyber-physical security requirements are sparse in current codes and standards and are much needed in areas such as the PKI system, data in flight, physical security, certification, and asset management to advance the security of the EV ecosystem. The entire length of the supply chain requires support from the ground up to enhance cybersecurity. This includes quality assurance of the design and manufacturing processes (including cryptographic materials), formal shipping processes, inspection of sample equipment arriving from external partners, and tracking of libraries and creation of golden images of software to check against tampering. EVSE manufacturer facilities should be thoroughly assessed including the back office, equipment, suppliers, etc. Best practices for the supply chain are required with an emphasis upon incorporation of cyber-physical security upfront in the design and manufacturing processes, not as an afterthought or implemented through retrofit which tends to lead to insufficiencies. Assessment of Federal and state regulations and laws is also needed to ascertain potential impediments to efforts to advance the cybersecurity posture of the EV ecosystem. Finally, upon completion of comprehensive gap analyses and need assessments, prudent investment prioritization must be identified and established. There are limited resources (financial and workforce) available to research, develop, and implement cybersecurity strategies and technologies. The following are five near-term priorities to advance gap analyses and needs assessments:

Portfolio of technology R&D: Identify and develop a prioritized list of system and technology R&D needs.

Codes and Standards: Assess codes and standards to identify high priority cybersecurity gaps, needs, requirements, and best practices.

Awareness: In concert with industry, further awareness of stakeholders within the EV-Grid ecosystem of the cybersecurity risk landscape, prioritization of high consequence events and mitigation strategies, and critical technology needs.

Supply chain: In concert with other Federal agencies, develop strategies for identifying and assessing supply chain cybersecurity vulnerabilities.

Federal and state regulatory landscape: Identify Federal and state regulations and laws and assess their status with regards to benefits and/or hinderances toward strengthening the cybersecurity posture of the EV ecosystem.

Research and Development: Significant advances are needed in the research and development portfolio of cybersecurity strategies, systems, technologies, and tools. Hardware and software are needed for perimeter defenses, intrusion detection and prevention, threat mitigation and isolation, and charging system recovery. Technologies are required which are interoperable and resilient. Open architectures and robust, retrofittable and scalable hardware and software cybersecurity technologies are necessary. Broadly speaking, R&D is needed in communication and control strategies and technologies, security approaches, and future proof design, elements of which are further identified below.

Communication and Control

Universal and trusted PKI for the EV/charging infrastructure

Standardized, baseline controls including access control, audit and accountability, identification, and authentication

EV/EVSE/smart grid and utility/aggregator communication and control

XFC site resource management control of on-site energy storage/generation and building energy management of microgrids

Open, interoperable, and scalable architectures for vehicle grid integration (e.g., Open Field Message Bus (OpenFMB), OpenADR)

Cryptography: data integrity and security to authenticate users, devices, and controllers attempting to access data and algorithms

Monitoring and analysis of communication misuse

Tools for machine-to-machine information sharing

Security Approaches

Situational awareness methods to detect, investigate, and remediate anomalies

Real time intrusion detection and prevention systems including monitoring signatures of potential intrusions and anomaly-based intrusion detection

Perimeter defenses including firewalls, access control lists, data in-flight requirements (encryption, node authentication, etc.)

Segmentation to separate and secure key components to prevent a vulnerability from compromising the whole system

Software and hardware for security hardened controllers, converters, and monitoring systems for XFC (>350kW) infrastructure, and secure sensing/actuation techniques

Defense-in-depth and learning-enabled moving-target defense

- Incident response mechanisms to prevent further adversarial actions on the system, non-repudiation technologies, attribution, and dynamic responses
- Hardware and software-based fallback and contingency operating modes
- XFC and wireless power charging threat protection
- Network fingerprinting to profile system behavior and device fingerprinting

Future Proofing

- Firmware assurance and compatibility of OTA software/firmware updates. Vehicle and EVSE firmware assurance and verification at time of installation, maintenance, and update
- Legacy versus new communication standards for EV/EVSE and lifecycle hardware requirements
- Real-time cyber health monitoring
- Forensics especially with regards to cross sectoral (EV/EVSE/grid) compatibility, integration, and analysis

The following are several key elements to advance the research and development portfolio of cybersecurity strategies, systems, technologies, and tools.

- Public Key Infrastructure: Support the Society of Automotive Engineers (SAE) and others in the understanding and development of a universal, widely accepted PKI.
- System and technology R&D: With stakeholder consensus, conduct R&D to advance high priority systems and technologies identified through gap and needs assessments.
- High power charging: Conduct R&D to assess the unique cybersecurity threats of high-power charging for medium- and heavy- duty vehicles and associated risks to the electric grid.

Testing, Validation, and Demonstration: Comprehensive, repeatable, and validated testing and evaluation is required for the development and verification of cyber defenses, especially at sectoral and systems interfaces. A cascading sequence of laboratory testing, field testing, and demonstration is needed to comprehensively assess cybersecurity systems and technologies. A number of entities within the government and the private sector have or are establishing cybersecurity testing requirements, protocols, and procedures for the EV ecosystem, but additional work is required in these areas. Additionally, DOE national laboratories, Department of Defense (DOD), NIST, Department of Homeland Security (DHS) and private sector entities maintain platforms and facilities for cybersecurity testing. However, there may be questions as to whether existing platforms and facilities are sufficiently aligned and compatible to enable comprehensive testing across the vehicle, charging, and grid interfaces and systems. Furthermore, greater third-party integration and certification services may be needed to assist and authenticate cybersecurity testing and validation processes.

Red teaming and penetration testing (or pen testing) are two means of assessing the cybersecurity of EVSE and connected systems. Red teaming is the practice of rigorously challenging cybersecurity plans, policies, systems, and assumptions by adopting an adversarial approach. Red teaming is a stealthy procedure that aims to test not only the system and protocols in place, but also the people who manage them. Red teaming is an advanced offensive security approach that mimics real-world attackers – from opportunists to Nation state actors. Often, a red team is a group of internal IT employees used to simulate the actions of those who are malicious or adversarial. Penetration testing is a manual security testing method that is used to provide a comprehensive overview of the quality and effectiveness of security control. The goal is to test the vulnerability of the networks, assets, hardware, platforms, and applications within a defined scope. Penetration testing targets specific attack vectors to understand how a system or procedure may be vulnerable to a modern attack. Penetration testing is typically performed against a predefined number of targets and is designed to test known exploits against known vulnerabilities. Figure II.42 presents a side-by-side comparison of elements of red teaming versus penetration testing.

Red Teaming	Penetration Testing
• Time-box for testing is extended • Team is encouraged to think creatively and use anything at hand for testing • Employees are usually not aware that testing is taking place • Testers seek to discover new vulnerabilities • Test targets are fluid and cross multiple domains • Systems are tested simultaneously	• Time-box for testing is brief • Testers use commercial pen test tools • Employees are aware that testing is taking place • Testers seek to exploit known vulnerabilities • Test targets are predefined • Systems are tested independently

Figure II.67. Comparison of Red Teaming vs Penetration Testing[154].

The following identifies two near-term priorities to further testing, validation, and demonstration of cybersecurity protocols, procedures, and countermeasures:

Cybersecurity testing, protocols, and procedures: Close identified gaps in cybersecurity testing, protocols, and procedures, as well as platforms and facilities if needed, across the EV ecosystem.

Cybersecurity countermeasures evaluation: Test, validate, and demonstrate the most promising cybersecurity countermeasures based on risk formulation (e.g., PKI, blockchain, hardware/software hardening, moving target defense, redundancy, etc.)

Activities

This following section presents a synopsis of Federal Government and private sector cybersecurity activities related to vehicles, charging infrastructure, and the electric grid. It is a challenge to comprehensively identify cybersecurity activities across the EV ecosystem, especially with regards to the private sector due to its sensitivities and proprietary nature, which limits availability of information to the public. Although not presented here, it is important to note that considerable cybersecurity activities are also being conducted by state agencies, associations, consortiums, and non-profits, as well as at entities overseas. At the end

[154] Red Teaming, Tech Target Contributor, April 21, 2021, [Online]: https://whatis.techtarget.com/definition/red-teaming.

of the section, specific discussion is provided on the NIST Cybersecurity Framework, SAE EV Charging PKI Project, and the DOE Cybersecurity Capability Maturity Model (C2M2).

Federal Government

DOE is conducting a broad spectrum of cybersecurity activities across four principal offices: the Vehicle Technologies Office (VTO), Office of Cybersecurity, Energy Security, and Emergency Response (CESER), Office of Electricity (OE), and the Office of Technology Transitions (OTT). Other DOE offices conducting cybersecurity related activities include the Office of Chief Information Officer (OCIO), Office of Building Technologies (OBT), the Federal Energy Management Program (FEMP), and the National Nuclear Security Administration (NNSA).

The G&I Program within VTO emphasizes cybersecurity risk and impact assessments, research and development, and testing and evaluation. The G&I Program is conducting a broad portfolio of adversarial-based threat risk assessments and impact analyses, prioritizing high consequence events based upon impact severity, and identifying mitigation strategies and solutions. Specific systems and technologies solutions are being researched and developed, and in some cases demonstrated. Open-source cybersecurity architectures are being developed for retrofittable, interoperable, and scalable security solutions. Robust, resilient hardware and software are being developed for sensing and actuating technologies, diagnostic security, and learning enabled, moving target defense. Red teaming and penetration testing of a broad spectrum of DCFC and XFC EVSE are also being conducted, as well as analyses of the impact of cybersecurity breaches on utility distribution and transmission systems. Recommendations are being provided with regards to the development of PKI systems and cybersecurity for supply chains. Finally, the G&I Program is working with NIST on a handbook of cyber-physical cybersecurity for EV charging and coordinating on risks and recommendations to further knowledge, tools, and capabilities to mitigate cyber-physical vulnerabilities, as well as collaborating to provide leadership and prioritize investments.

CESER undertakes broad cybersecurity related activities of relevance to electric vehicle to grid integration. The CyOTE project under the CESER Threat Mitigation Program researches tools, tactics, and techniques to correlate anomalous activities with possible threats. Developments from this work are applicable to threat detection and mitigation with regards to V2G integration. The C2M2 Program is applicable to this field and coupled with the ongoing work from CESER in advancing developments of cybersecurity frameworks in the energy sector. The CESER funded R&D portfolio also includes work for advancement in microgrid cybersecurity and key encryption and distribution. The FY21 Appropriations Bill includes language directing CESER to fund a pilot project to demonstrate cybersecurity best practices and collaborations in deploying and operating cybersecure EV charging facilities. CESER plans to collaborate with DOE's EERE to fulfill this requirement.

In the Fall of 2021, NIST undertook an interagency agreement with DOE to expand upon prior work conducted by DOE and EPRI to develop a cybersecurity platform and certification framework for an extreme fast charging XFC – integrated ecosystem. The NIST National Center of Excellence (NCCOE) will expand upon this work from DOE/EPRI and align the cybersecurity controls recommendations with the NIST cybersecurity framework (CSF). NIST will create a CSF for an XFC infrastructure profile, including an XFC, EV, XFC-Cloud or third-party operator, and XFC and Utility-Building network. The focus will be on research and development of a CSF profile, standards best practices, and practical guidance for organizations and stakeholders engaged in designing, building, installing, and/or operating XFC infrastructure. This CSF Profile is non-mandatory and is intended as guidance to entities engaged in the development of a national-level risk-based approach for managing cybersecurity activities for an XFC ecosystem. The effort was funded in FY22 and is expected to generate a draft 'Cybersecurity Framework Profile for EV XFC Infrastructure' document in FY23.

The Department of Homeland Security (DHS) and the Department of Transportation (DOT) are co-lead agencies for cybersecurity for the Transportation Systems Sector. The DHS Science and Technology Directorate (S&T) cyber mission contributes to enhancing the security and resilience of the Nation's critical information and internet by: developing and delivering new technologies, tools, and techniques to enable DHS and the United States to defend, mitigate, and service current and future systems, networks, and infrastructure against cyber-attacks; conducting and supporting technology transition; and leading and coordinating R&D among the R&D community which includes DHS customers, government agencies, the private sector, and international partners. DHS maintains cybersecurity projects in over twenty areas.

Within the DOT, the Federal Motor Carrier Safety Administration (FMCSA), Volpe National Transportation Systems Center (Volpe), National Highway Traffic Safety Administration (NHTSA), and DOT's Intelligent Transportation Systems Joint Program Office (ITS JPO) are conducting cybersecurity related activities. FMCSA has developed cybersecurity best practices for integration and retrofit of telematics and aftermarket systems into heavy vehicles. Volpe has developed a heavy-truck cybersecurity research inventory, supports cyber physical systems security for DHS's automotive cybersecurity program, develops guidance on the vulnerabilities in telematics and fleet management systems, and conducts vulnerability testing of telematics devices. NHTSA has developed a multi-faceted research approach that leverages NIST's CSF and encourages industry to adopt practices to improve the cybersecurity posture of their vehicles in the United States. NHTSA's approach includes four main areas: protective and preventive measures and techniques, real-time intrusion (hacking) detection measures, real-time response methods, and assessment of solutions.

The 2018 DOD Cyber Strategy represents DOD's vision for addressing cyber threats and implementing the priorities of the National Security Strategy and National Defense Strategy for cyberspace. Within DOD, the U.S. Army Combat Capabilities Development Command (DEVCOM) Ground Vehicles Systems Center (GVSC), Defense Logistics Agency (DLA), Defense Applied Research Projects Agency (DARPA), and the Naval Facilities Engineering Command (NAVFAC) conduct vehicle and charging system cybersecurity related activities. The DEVCOM GVSC mission is to ensure existing tanks, trucks, and ground systems are secure against cyberattack and to develop new systems using resilient engineering structure from the ground up. The DEVCOM GVSC cyber hub is maintained at the Detroit Arsenal in Warren, Michigan. The DLA's cyber resilience activities include cyber resilience integration, operational technology, contingency planning, supply chain criticality, and cyber resilience mitigation strategies. DARPA is focused upon three main cybersecurity priorities: making systems more secure and resilient; improving situational awareness; and improving the military's ability to strike back in a precise, tactical manner. NAVFAC is currently focused on cybersecurity best practices and procurement language for EVSE for use by asset owners, operators, integrators, and suppliers.

Private Sector

The private sector is extensively involved in cybersecurity for the EV ecosystem. The Auto Information Sharing and Analysis Center (Auto-ISAC), established and run by the Cybersecurity and Infrastructure Security Agency with oversight by DHS, is an industry-driven community to share and analyze intelligence about emerging cybersecurity risks to the vehicle and to collectively enhance vehicle cybersecurity capabilities. The Auto-ISAC includes LDV and HDV OEMs (including the autonomous industry), suppliers, and the commercial vehicle sector. The Auto-ISAC covers a broad portfolio of cybersecurity related activities including vulnerabilities, threat feeds, research, best practices, intelligence, trends, forecasts, and data feeds, as well as conducting validation, analysis, impact assessment, and pattern identification. The Electricity Information Sharing and Analysis Center (E-ISAC) serves as the primary security communication channel for the electricity industry and enhances industry readiness and its ability to respond to cyber and physical threats, vulnerabilities, and incidents. The E-ISAC gathers and analyzes security data, shares appropriate data with stakeholders, coordinates incident management, communicates mitigation strategies with stakeholders, and serves as a central point of coordination and communication for members.

Many automobile and heavy-duty truck OEMs, EVSE CNOs, and EVSE manufacturers are independently conducting cybersecurity-related activities. This includes development of best practices, requirements, and guidelines; and conducting threat, risk, and impact assessments. Communication and control activities are being pursued including XFC site resource management control of on-site energy storage and generation; data integrity and security methods to authenticate user, devices, and controllers; V2X communications; and end-to-end EV/charging infrastructure trust models. Other areas being pursued include denial of service to charging stations and vehicles; XFC and wireless charging threat protection; hardware/software hardening; and EVSE intrusion detection/mitigation, strategies, and tools. Testing and evaluation are being conducted including firmware assurance and verification at time of installation and maintenance, and EV/EVSE system forensics.

Utilities and universities are conducting wide ranging vehicle/EVSE/grid cybersecurity related activities. Some utilities are utilizing the NIST CSF based assessments to form a more robust cybersecurity posture. A number of areas are being pursued including isolation for internet facing technology service layers, centralized monitoring and response, nonrepudiation of system activity; grid system network segmentation; operational alignment with technology; and legacy-grid system capability. Other examples of areas being explored include device access controls, user access controls, malware protections, vulnerability management, data encryption services, system monitoring services, and defense-in-depth strategies. Some forward-looking utilities are looking to remain abreast of changes in the regulatory landscape and follow Critical Cyber Assets in the NERC Cyber Security Standards, Critical Infrastructure Protection (CIP) 006, as well as industry standards from NIST such as those outlined in the industry guideline NISTIR 7628, Guidelines for Smart Grid Cyber Security. Universities are also active in cybersecurity for the EV ecosystem and are working on a broad variety of cybersecurity related activities. This includes risk and vulnerability assessments, insider threat modelling, V2X data exchanges, compromise-resilient software update security systems for EVs, and in-vehicle platform security design. Other areas of attention are intrusion detection and protection systems, sensor spoofing manipulation, resiliency and recovery, cryptography, software security, and multi-prong security features to prevent vehicle cyber-attacks at varied points of entry (e.g., car manufacturers, dealerships, internal software developers, etc.).

Projects

The NIST Framework for Improving Critical Infrastructure Cybersecurity (Cybersecurity Framework) can be considered a best practice that describes a holistic approach to mitigating cyber threats across complex systems consisting of three parts. The Framework consists of five concurrent and continuous functions: Identify, Protect, Detect, Respond, and Recover (see Figure II.43).

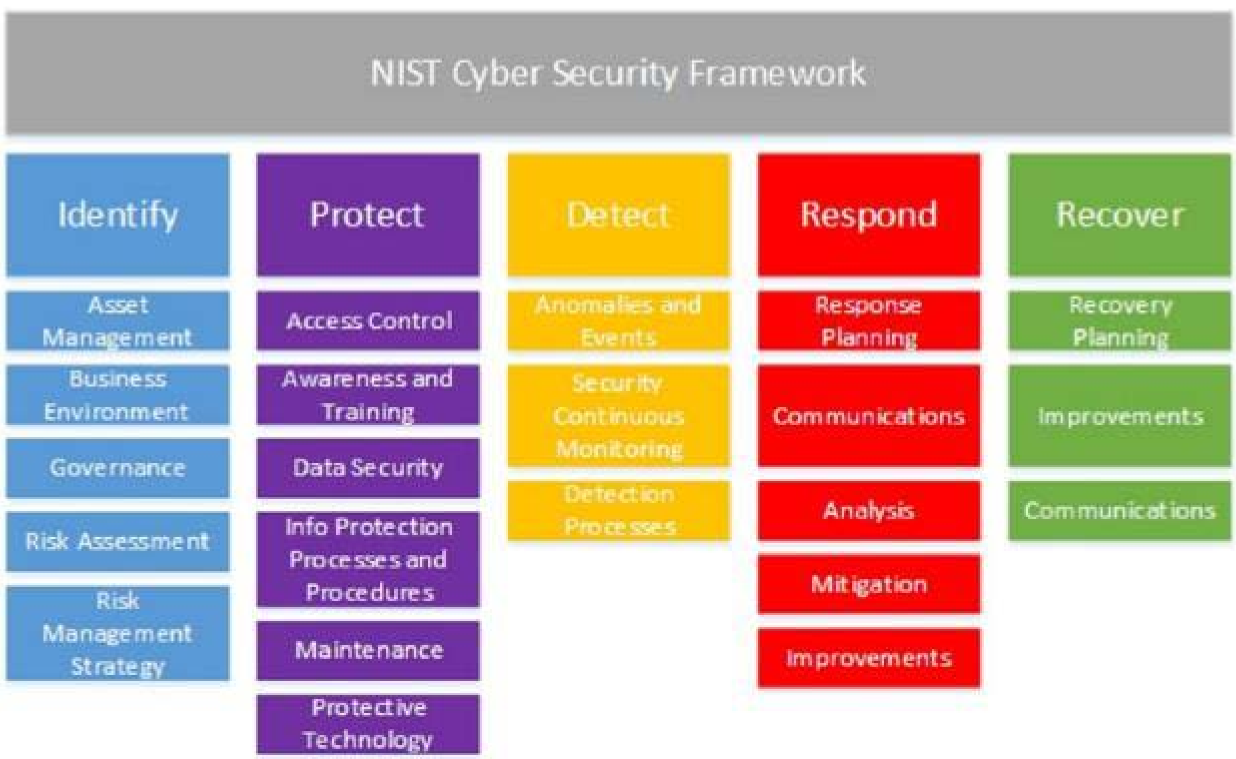


Figure II.68. NIST Cyber Security Framework.

This framework provides an outline of critical areas to address with regards to cybersecurity, and when considered together these functions provide a high-level, strategic, lifecycle view of cybersecurity risk. The Framework Core is a set of cybersecurity activities, outcomes, and information references that are common across sectors and critical infrastructure. The Framework Core identifies underlying key categories and subcategories which are discrete outcomes for each function. The second part, Implementation Tiers, provide mechanisms for organizations to view and understand the characteristics of their approach to managing cybersecurity risk which will help in prioritizing and achieving cybersecurity objectives. The third part, Framework Profiles, can be characterized as the alignment of standards, guidelines, and practices to the framework core for implementation scenarios and business requirements. Overall, the Framework provides a common taxonomy and mechanisms to describe the current cybersecurity posture, identify the target state for cybersecurity, identify and prioritize opportunities for improvement, assess progress toward the target state, and communicate among internal and external stakeholders about cybersecurity risk. The best practices of the NIST Framework will be instrumental in helping structure the governmental response to the cybersecurity challenges facing the EV ecosystem.

In August 2020, SAE kicked-off the EV Charging PKI Project which is an industry-led pre-competitive research effort to strengthen EV charging system security. The project will design and test an inclusive, worldwide EV charging industry PKI platform that is secure, trusted, scalable, interoperable, and extensible. The final EV Charging PKI platform design will be a simple, yet powerful PKI solution, equipped with advanced certificate and key management functionality, solid governance, cryptographic agility, scalability, and network security required by the EV charging ecosystem. The project will provide a handover plan for fielding and operating a full-scale, industry-wide PKI platform. As part of this project, an industry PKI review and gap analyses was undertaken which assessed the ISO 15118-2 and -20 protocols, Verband Deutscher Elektrotechniker (VDE) and CharIN industry guidelines for Plug-n-Charge, ChadeMO standards, and conducted interviews with SAE cooperative research project stakeholders.

A 360-degree PKI assessment methodology (gap analysis) was conducted of the ISO 15118-2 and -20 protocols and cybersecurity to ensure comprehensive consideration of the governance, technology, and operational requirements to be captured in the PKI platform requirements and design (see Figure II.44). Here, each of the three major categories (i.e., governance, technology, and operations) are examined in detail, with components (subtopics of each major category) given a maturity ranking and goal, and subsequently elements (specific topics of each component) providing ranking information to evaluate component maturity. The PKI platform design with an operational PKI is expected in October 2021, followed by PKI platform testing in Winter 2022 at NREL, and an open HackFest in Spring 2022. The goal is to test the readiness of the PKI, identify gaps between existing requirements and best practices, and identify any further vulnerabilities that can be mitigated to advance the design of the PKI platform. The PKI platform is designed with the entire EV charging ecosystem in mind, flexibility to be compliant with ISO 15118-2 and -20, and is likely to include a plan for the governance structure of the PKI.

In July 2021, DOE released Version 2.0 of the C2M2, a tool designed to help companies of all types and sizes evaluate and improve their cybersecurity capabilities. The C2M2 is managed by

DOE's CESER and provides descriptive rather than prescriptive guidance. The C2M2, first released in 2012, is designed to help energy sector organizations understand cyber risks to their information technology (IT) and operational technology (OT) systems and measure the maturity of their cybersecurity capabilities.

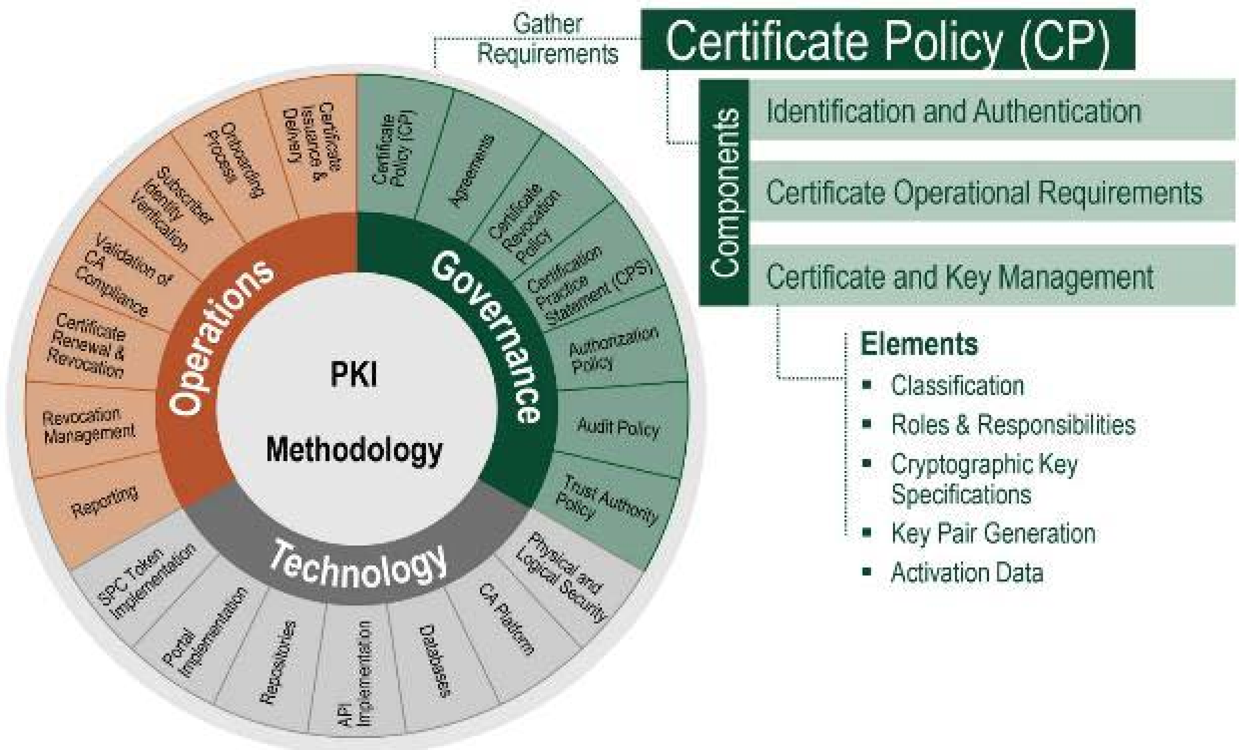


Figure II.69. 360-degree Public Key Infrastructure (PKI) Assessment Methodology[155].

The updated model addresses new technologies like cloud, mobile, and artificial intelligence, and evolving threats such as ransomware and supply chain risks, and ultimately supports companies in strengthening their operational resilience. The C2M2 comprises domains, objectives, practices, and maturity indicator levels (MILs). C2M2 domains include Asset, Change, and Confirmation Management; Cybersecurity Architecture; Cybersecurity Program Management; Event and Incident Response, Continuity of Operations; Identity and Access Management; Risk Management; Situational Awareness; Third-Party Risk Management; Threat and Vulnerability Management; and Workforce Management. Objectives represent cybersecurity achievements that may be accomplished by implementing the practices in the domain. Each set of practices represents the activities an organization can perform to establish and mature capability in the domain. To measure progression, the C2M2 uses a 1-3 scale of MILs, with each representing maturity attributes. Organizations that implement the cybersecurity practices within each MIL achieve that level. The C2M2 is designed for use with a self-evaluation methodology and tool.

[155] SAE International Electric Vehicle PKI – EPRIWG Presentation, eonTi and digicert, March 25, 2021.

Takeaways

- A lack of cybersecurity has the potential to be a major impediment to the large-scale adoption and integration of EVs with the grid.
- The vast cross-sectoral nature of the EV ecosystem, combined with the complexity of systems and technologies required to integrate EVs onto the grid, exposes a multitude of cybersecurity vulnerabilities.
- Cybersecurity must be continually addressed as no EV ecosystem will ever be entirely secure and threats will continually evolve.
- As communication networks for EVs, EVSE, and external systems increase, the attack surface also increases, leaving the charging infrastructure and wider EV ecosystem more open to exploitation of cybersecurity vulnerabilities.
- Cybersecurity breaches can affect the operation of the transportation sector by limiting the ability of charging equipment to function, expose personally identifiable and financial information, and more ominously affect safe operations during charging and vehicle operation.
- A compromised charging infrastructure can pose a major threat to the electric grid. A large-scale synchronized attack can affect large portions of the grid simultaneously. A localized cyber-physical attack can lead to a sudden addition or reduction of load creating voltage imbalances and undesirable power quality impacts resulting in local disruptions such as brownouts, damaged equipment, and market disruptions.
- A holistic cybersecurity approach will require significantly greater harmonization across many sectors and major advances throughout the portfolio of systems, technology, and tool development.
- Addressing the cybersecurity challenges will require stakeholder engagement, coordination, and consensus; gap analyses and needs assessments; research and development; and testing, validation, and demonstration.

Recommendations

- DHS could establish leadership in EV charging cybersecurity by creating a cross-sector Information Sharing and Analysis Center (ISAC) specifically for the EV charging ecosystem. This ISAC could integrate efforts from the Auto-ISAC and E-ISAC.
- DOE, in collaboration with NIST, DHS, and other Federal agencies, could convene stakeholders to identify key cybersecurity challenges and vulnerabilities to inform the development of a comprehensive cybersecurity roadmap for EV charging and grid integration.
- DOE could expand activities to work with other Federal agencies and stakeholders to advance cybersecurity education and workforce development for EV charging and grid integration.

- DOE could expand activities to continue to support stakeholder assessments of codes and standards to identify high priority cybersecurity gaps, needs, requirements, and best practices.
- DOE could expand activities to increase the awareness of the cybersecurity risk landscape; prioritization of high consequence events and mitigation strategies; and critical technology needs amongst EV grid stakeholders.
- DOE in concert with NIST, and other Federal agencies, could expand activities to develop strategies for identifying and assessing supply chain cybersecurity vulnerabilities and mitigation strategies for EV charging and grid integration.
- DOE could expand activities to support SAE and others in the development of a widely accepted PKI for the EV charging ecosystem.
- DOE could expand RDD&D activities on charging cybersecurity technology solutions to threats on light-, medium-, and heavy-duty vehicle charging and associated risks to the electric grid. These solutions could include identification, protection, detection, response, and recovery. The most promising cybersecurity solutions should be tested, validated, and demonstrated.
- The Federal Government could support the establishment of cybersecurity testing procedures, platforms, and protocols to strengthen EV charging stakeholders' cybersecurity posture.

F. An assessment of the feasibility of adopting technologies developed under the program established under subsection (a) at Department facilities

DOE is the leading institution for research and innovation for advanced EV charging, charge management, and grid technologies and is leveraging its facilities for the demonstration and validation of systems and technologies developed at DOE national laboratories. This requires the coordination of not only DOE fleet and facility operations, but also coordination with each electric utility providing service to the facilities. These demonstration activities can also be structured to encourage participation by DOE and contractor staff that own their own electric vehicles and drive them to DOE facilities.

DOE is similar to most other Federal agencies in the composition of its vehicle fleet. The DOE fleet is comprised of light-, medium-, and heavy-duty vehicles that are a mix of agency-owned and General Services Administration (GSA) leased vehicles. The vast majority are light-duty passenger cars and trucks leased from GSA. GSA is working to expand the offerings of PHEV and EV models available to Federal fleets and the number and types of EVSE available. The DOE fleets will continue their efforts to evaluate vehicle mission needs against the available options from GSA and work towards electrification of their fleets. As part of this process, the fleet managers will work with their facilities' managers and electric utilities for the installation of necessary charging equipment.

While the above process may take several years to complete, DOE researchers are working with their facilities' managers to demonstrate and validate DOE developed SCM and VGI systems and technologies. In most cases, these demonstrations are set up to take advantage of the more rapid adoption of electric vehicles by DOE staff and contractors. For example, Argonne National Laboratory has installed a mix of AC Level 2 and DC fast chargers integrated with PV and stationary storage at the Smart Energy Plaza, which is a research center focused on VGI. Here, advanced SCM techniques were employed to study their effectiveness in providing grid services by controlling the charge rates and power levels of DOE employee and contractor vehicles that were charging at the facility. Another example, the National Renewable Energy Laboratory has deployed 108 AC Level 2 chargers and one 25 kW wireless charger, incorporating a smart charge management program designed to keep the overall facility load below demand charge limits. The SCM controls the vehicle charging during the day while still meeting the charging needs of employees. While both examples primarily relied on non-DOE owned or leased EVs for demonstration of VGI, the Department is committed to utilizing its facilities as innovation hubs which can integrate DOE vehicles into these and other VGI programs as the DOE fleet transitions to EVs.

Takeaway

It is feasible to adopt DOE developed SCM and EV-Grid integration solutions at DOE facilities.

Recommendations

DOE could expand activities to utilize its facilities for the validation and demonstration of SCM and EV-Grid integration solutions developed by the Department.

III Recommendations

A. Assessment Study Results Takeaways and Recommendations

As background material for the 10-year roadmap to guide the research, development, and demonstration program to integrate electric vehicles onto the electric grid that is described later in this section, the table below (Table III.1) contains the takeaways and recommendations for each subsection of the study results (Section II). The recommendations contained in Table III.1 below are intended to complement the 10-year VGI roadmap to implement the Department's VGI Initiative. In this table each subsection has two rows of information. The first row contains the takeaways, and the second row contains the recommendations for each subsection of the assessment study results.

Table III.5. Takeaways and Recommendations for Each Study Results Sub-Section.

Study Results Section Number and Subject	*Takeaway/Recommendations*
II.A.0 Use of electric vehicles to maintain the reliability of the electric grid – Takeaways	EVs are transportation devices first. While they often have significant idle time, especially in residential settings, their availability for grid-reliability-improving services may not be available when needed. Advanced EV charging controls have been developed to help provide grid services that improve reliability, but have only been evaluated in simulation or small-scale demonstrations in the U.S. Vehicle manufacturers are starting to have more vehicle-to-building (V2B) offerings, allowing the customers to use them for backup power to improve their reliability (See Section II.C.vi for details). The reliability cost-to-benefit ratios of EV grid services are still relatively high, due to limited deployments and the novelty of the technology. Many of the advanced EV controls to improve reliability will require more communications and aggregation of the EVs, opening up new cybersecurity scenarios and unveiling a new attack plane/vector (See II.E for details). EVs are complicated devices, with many components and supply streams. If they become a significant resource for maintaining grid reliability, supply chain assurances (both in availability and cyber-physical considerations) may need to be evaluated (See Section II.E for details).
II.A.0 Use of electric vehicles to maintain the reliability of the electric grid, – Recommendations	DOE could expand activities to coordinate with, and support Industry efforts to enable the leveraging of EVs in an overall DER framework. In support of this activity, DOE could quantify and qualify the benefits of EVs to support grid reliability. EVs and other DERs will probably require new reliability metrics to be developed. DOE and private entities could expand activities

	cooperatively investigate new reliability metrics to capture the impacts of customer-provided and novel technology DER services, including those from EVs. Adoption of EVs@Scale and adoption of VGI capabilities may reduce costs of reliability services due to economies of scale. DOE could expand activities to perform demonstrations to valuate and enable adoption of these capabilities.
II.A.i Use of electric vehicles for demand response, load shaping, emergency power, and frequency regulation – Takeaways	EVs have the capability to provide various grid services that support grid reliability. While EVs can be used to support the grid, an electric vehicle's primary purpose is mobility. Ultimately the owner will determine how to deploy its capabilities (as transportation or DER). EVs providing grid services will depend on the availability of the vehicle (Section II.C.ii), the existence of incentives (section II.C.v), and the implementation of enabling technologies. Certain grid services will require other technologies, such as controllable V1G or V2X-enabled EVSE, SCM, or DERMs.
II.A.i Use of electric vehicles for demand response, load shaping, emergency power, and frequency regulation – Recommendations	DOE could expand activities to conduct RDD&D on furthering and optimizing the capability of EVs and EVSE to provide grid services and accelerate market adoption.
II.A.ii Reuse of spent electric vehicle batteries for stationary grid storage – Takeaways	The vision for using spent EV battery packs has merit but faces significant barriers to market viability that must be resolved.
II.A.ii Reuse of spent electric vehicle batteries for stationary grid storage – Recommendations	DOE could establish RDD&D projects to develop tools and standard procedures to assess state of health (SOH) at the cell, and pack level, and predict future battery degradation related to second use applications. The diagnostic capabilities would help the industry address the specific requirements of UL 1974 by assessing the health status of the pack and would predict the reliability of each pack. DOE in cooperation with industry stakeholders could conduct RD&D to mitigate factors that cause thermal runaway in battery packs in transit, which will improve public safety and minimize transportation costs of spent packs. DOE could support industry in developing methodologies to establish a historical record of on-board usage by collecting data on pack operations and operating environments. DOE could also play a

	critical role to encourage industry to create a standard EV battery pack usage data set and open interface protocols to access the usage history for any given battery pack. DOE could conduct a study working with industry to evaluate and quantify thermal management needs associated with secondary use of spent EV batteries for stationary storage applications.
II.B.i- Impact of bi-directional electricity flow on battery degradation – Takeaways	Battery degradation is impacted by both the use case for V2X and the vehicle utilization. There will not be a single result for whether V2X degradation is either negligible or significant. There is great uncertainty of the potential impacts of V2X on the traction batteries and more independent testing and data are needed before vehicle manufacturers will make bi-directional operation widely available.
II.B.i- Impact of bi-directional electricity flow on battery degradation – Recommendations	DOE could conduct further studies of the degradation impact on batteries under various V2X operations to develop confidence in the capabilities of EVs to provide V2X services. DOE could develop cell chemistry design approaches that will minimize impacts of V2X operations on EV batteries. DOE, working with industry stakeholders, could develop models and tools, such as machine learning and artificial intelligence, to accurately estimate degradation for specific use cases and predict the value of V2X participation. Vehicle manufacturers could develop and deploy intelligent control for EVs that is designed for one or more use cases and can balance the degradation effects of additional cycling due to V2X for different battery technologies. These technologies could play a critical role in alleviating consumer and manufacturer warranty concerns.
II.B.ii- The implications of the use of electric vehicles for grid services on original equipment manufacturers - Takeaways	EV warranties are a mechanism used to protect the economic and safety interests of EV owners and EV OEMs. EV-Grid integration stakeholders need to understand the underlying concerns that may cause an EV OEM to nullify the warranty when the EV is used to provide V2X services. EV-Grid integration needs to address the technologies, tools, and data necessary for developing integrated technologies that are safe, mutually beneficial, and viable.
II.B.ii- The implications of the use of electric vehicles for grid services on original equipment manufacturers - Recommendations	DOE could work with stakeholders to collect data on the degradation of batteries due to V2X operations in the most likely operating use cases, perform analyses on the data collected, and make the data set and analyses results available to EV OEMs.
II.C.0 Impacts to the electric grid of	The addition of EVs onto the electric grid represents an increase in overall loading on the system.

in-creased penetration of electric vehicles – Takeaways	Aging and insufficient infrastructure is more likely to cause problems at the distribution level as this significant EV load is added to the system. As the penetration of EVs increases, there is potential for the impacts of the additional devices to create both problems and opportunities at all levels of the power system (distribution, subtransmission, and transmission), which will require more investigation at both the local and system levels.
II.C.0 Impacts to the electric grid of in-creased penetration of electric vehicles – Recommendations	Detailed in subsections II.C.i through II.C.vii Recommendations below.
II.C.i Distribution grid infrastructure needed to support an increase in charging capacity – Takeaways	Generation capacity (amount of power produced) is not a major constraint in EV integration and could be managed while infrastructure upgrades occur, but capacity constraints on moving the power from the generators to the loads (the transmission and distribution infrastructure) is currently a more significant limiting factor and will continue to be a complex problem to address. Areas with lower distribution operating voltage often have the most difficult EV integration challenges. These distribution systems are often older, in less affluent areas, and represent areas where EV integration may have more pronounced greenhouse gas emission impacts. The variations of the distribution network (voltage, size, loading, age, etc.) can lead to grid issues when integrating EVs and can have a profound impact on charging infrastructure integration strategies. Submetering associated with integrating EVs is evolving, with existing standards being leveraged and new standards being developed, primarily for billing and revenue-grade applications associated with EV charging.
II.C.i Distribution grid infrastructure needed to support an increase in charging capacity – Recommendations	DOE could expand activities to work with the transportation industry and electric utilities to develop and continue refining forecasting models for customer EV charging behavior (time, location, willingness to participate in grid services) to help infrastructure planners anticipate the evolving landscape. DOE could expand activities to work with electric utilities to help coordinate the integration of EVs into an overall optimized DER framework (high renewable DER adoption) to not only promote management of the increasing population of EVs, but also generalize them as another resource to allow utilities easier integration into their operating procedures.

	DOE could expand activities to conduct research on technologies to facilitate EV charging integration in areas with limited grid capacity. DOE could expand activities to help stakeholders to identify capacity constraints in locations where transportation electrification will likely require charging infrastructure buildout. DOE could expand activities to work with stakeholders to help develop standards for metering requirements on EVs, especially in the context of providing appropriate information for EV use in grid services.
II.C.ii Strategies for integrating EVs – Takeaways	There are multiple strategies that can be used to minimize grid infrastructure upgrades necessary for EV charging. Each strategy offers different applicability, costs of implementation, and value. There are planning strategies for the intelligent location of charging infrastructure and operational strategies to control charging that minimize grid upgrades. These strategies leverage the charging time and location flexibility of EVs. These strategies should also consider population density, vehicle travel patterns, land use, current and projected risk from natural hazards, and disadvantaged community census tracts (using the CEJST) to equitably distribute EVSE.
II.C.ii Strategies for Integrating EVs – Recommendations	DOE could expand activities to conduct further analyses and demonstration of Vehicle Grid Integration strategies to determine value and effectiveness when deployed in common use cases as well as less common evacuation and emergency preparedness use cases.
II.C.iii- Charging 24h Demand – Takeaways	The charging behavior of uncontrolled EVs can change the 24-hour electricity demand increasing peak load or potentially shifting when a peak may occur. These changes in demand will differ at the feeder-level and across a wide-scale metropolitan area. Charge management strategies to influence EV charging behavior can be very effective in changing the 24-hour demand profile and strategies should consider the approach holistically to prevent unintended secondary effects. Charge management strategies to shift charging behavior are dependent on both charge location and charge time flexibility, noting that each are respectively reliant on charging infrastructure deployment and vehicle travel constraints.
II.C.iii- Charging 24h Demand – Recommendations	DOE could expand activities to evaluate the effectiveness of charge management strategies to identify which strategies provide the most value to the grid, especially for future EVs@Scale adoption. DOE could analyze how EVs can enable greater integration of clean DER to benefit the grid by shifting demand.

	DOE could expand activities to further study the potential for V2X capable vehicles to benefit the grid through shifting load in the 24-hour demand by leveraging their storage capability.
II.C.iv Load Increases from Electrifying Vehicles – Takeaways	It is expected that energy generation and capacity requirements can be managed with proper planning for EV penetration and resulting charging demand to support a growing EV fleet. Although the issues vary geographically and are use-case specific, they do not undermine the overall conclusion that at the generation level EVs@Scale will not prove a significantly greater challenge than past evolutions of the U.S. electric power system. Transmission and distribution; however, may prove to be significantly greater challenges and need considerably more assessment to identify constraining aspects and will require innovative and proactive solutions and strategies.
II.C.iv Load Increases from Electrifying Vehicles – Recommendations	DOE could expand activities to work with all stakeholders (which includes community and environmental justice representation) to develop tools for assessing the impacts of high-power charging of light-, medium-, and heavy-duty vehicles on utility distribution and transmission systems. DOE could expand activities to assess the ability of innovative strategies to minimize the impacts of the adoption of EV infrastructure on distribution grids in dense urban, rural, capacity constrained areas, including disadvantaged communities, and tribal lands. DOE could expand activities to conduct further analyses of medium- and heavy-duty EV market growth scenarios and impacts on energy generation and energy capacity. DOE could expand activities to assess the implications to the grid of new high power charging technologies as they are developed by industry. DOE could support utilities in their planning of, and manufacturers supporting the supply of transformers and grid components to expand the capacity of the transmission and distribution grid.
II.C.v Customer Incentives Managed Charging – Takeaways	A portfolio of incentive options will be necessary, but as significant EV adoption develops it may require more sophisticated approaches that include locational and temporal elements and can provide more refined control and dispatching strategies. Establishing incentive signaling early in the EV adoption path establishes customer expectations that are critical to behaviors necessary to support high EV penetrations. The increased value of more sophisticated incentive approaches will have corresponding increases in costs and complexity, but in some cases the value may far offset the costs.

	Customer behavior can be unpredictable and how they will respond is still unclear and requires additional research. Early adopters' behavior, and findings based on their behavior, might not represent behavior of the general population. The customer experience with incentives should be easy and seamless. Education will also be important for effective pricing implementation, customer preferences (e.g., signaling when renewables are dominant on the grid or in need of demand), and customer satisfaction. Rates can be an effective mechanism for incentivizing customer behavior but require advanced metering infrastructure to implement. Addressing customer preferences via highly varying rates will require availability of dynamic information and automation to meet those preferences, and those information needs will propagate across other actors in the system. Transactive energy markets do not currently exist at the distribution level where more complex approaches, such as real-time pricing or grid services markets, will likely be necessary.
II.C.v Customer Incentives Managed Charging – Recommendations	DOE could expand activities to provide technical assistance to stakeholders to improve local and regional EV adoption tools, across light-, medium-, and heavy-duty classes, that forecast grid impacts and can assist in development of appropriate incentives that balance grid and customer benefits. DOE could expand activities to advance Information usability for customers and other stakeholders which will require more development of machine-readable incentives such that software and people can easily incorporate incentive signals into their behavior. In collaboration with stakeholders, DOE could perform research to inform the design of equitable rates and incentives that are attractive to future customers and grid operators. DOE could develop and demonstrate optimization algorithms to assist with development of dynamic pricing incentives and transacting V2X at the distribution level. DOE could evaluate tools and strategies as well as conduct demonstration projects to mitigate information asymmetry across key system actors to help facilitate customer preferences (e.g., prioritizing carbon-free generation) and leverage incentives for transactive services. DOE could expand activities to conduct demonstration projects to evaluate and help address regulatory, policy, and market barriers to enable development of effective incentives to utilize EVs to provide load flexibility for bulk power and distribution system services.

	DOE could expand activities to support development of a standard specifically for metering EV energy usage, to allow for development of EV incentive structures, that is recognized and accepted by utilities and other entities, especially in areas with special rates, programs (including low income assistance programs), or controls for those EVs. DOE could provide assistance in valuation of SCM capabilities and financial mechanisms that enable market access (e.g., compensation mechanisms) DOE could evaluate and advance commercialization strategies and tools, and conduct demonstration projects to reduce barriers to V2X such as enabling third-party aggregation, evaluating innovative ownership models, streamlining interconnection, reducing interconnection costs where possible, and other business models, valuation, policy, and other protocols, etc.
II.C.vi V2X Tech – Takeaways	V2G capable EVs provide additional grid services potential. However, the customer and vehicle manufacturer benefits must be present in order for these opportunities to exist. V2X capable EVs could provide backup power, black start, and restoration services. The basic technology has been proven and pilot commercial offerings are becoming available. However, commercially available, certified products, and the business model are still being developed and warrant further investigation. Bi-directional capability is currently enabled only through the DC charging connections which are expensive and limited in availability in the United States. This also requires associated hardware to be deployed at any desired V2X site, while bi-directional capability through the AC connection may enable greater flexibility in the location where this can be applied to the power system but increases the size, weight, and cost of EVs. More research is needed to confirm the value of monetizing V2X capable EVs and the trade-offs to battery degradation. V2X capable EVs could be used to help maximize and optimize renewable energy usage. A holistic understanding of the complete V2X capable EV life cycle is needed.
II.C.vi V2X Tech – Recommendations	DOE could conduct RDD&D and help commercialize technologies (e.g., leveraging Artificial Intelligence/Machine Learning) to optimize V2X, including dynamic pricing and transacting V2X at the distribution level. DOE could expand activities to conduct research to confirm the value of monetizing V2X capable EVs and the trade-offs to battery degradation. Work with vehicle OEMs to address warranty

	concerns regarding potential battery degradation from bi-directional operations. DOE could conduct techno-economic analysis to identify thresholds to inform viable V2G business models for wholesale market grid services. DOE could expand activities to conduct RDD&D to maximize and enable optimal use of renewable energy sources by leveraging V2X capable EVs. DOE could expand activities to assist in large-scale pilot programs to evaluate V2X business models, market access, ownership models, customer incentives and behavior of different bi-directional capabilities and service offerings. This will include determining how much and where to deploy V2X capable EVs and EVSE. The results of these activities could inform and support community based V2X projects. DOE could collaborate with NIST, SSOs, and manufacturers to inform product certification standards that enable V2G interactions with the electric grid (e.g., UL certification), while ensuring consistency with other DER. DOE could conduct a techno-economic analysis of AC and DC based V2X. DOE could conduct education and outreach to educate state and local oversight bodies, consumers, building mangers, utilities, and other stakeholders about the potential cost benefits of V2X and various approaches to deployment. These stakeholders include community, transportation, and utility rate advocates.
II.C.vii SCM Techniques – Takeaways	SCM can support a range of vehicle classes and charging scenarios to benefit EV users as well as the grid, but challenges to implementation include the lack of smart communication capability in many current EVs and the use of proprietary communication by EVSE manufacturers and charging network providers. Proprietary communication limits the ability to integrate EVs and EVSE in local energy management schemes to benefit individual EV owners, workplaces, or public charging stations/plazas. Though proprietary communication is an understandable element of a charging network's business model, it must be addressed if SCM is to be implemented locally (e.g., workplace or building energy management systems) or across multiple charging networks. Several different communication pathways and protocols are being considered to implement SCM for residential, workplace and fleet charging scenarios. DOE research is addressing challenges to SCM of LDVs, including projects focusing on grid level analysis and smart charging strategies for EVs at scale as well as development and

	demonstration of smart charging ecosystems and enabling technologies on the customer side of the grid. Several challenges remain to be addressed for commercial MDVs and HDVs with the potential to support SCM. Respondents to the DOE RFI on VGI supported SCM and reinforced the dependency on standard protocols and interoperability of EVs, EVSE and charging networks/grid operators.
II.C.vii SCM Techniques – Recommendations	DOE could expand activities to develop and demonstrate VGI/SCM approaches to reduce grid impacts of on-road light-, medium-, and heavy-duty EV charging. Vocation-specific SCM strategies could considered, including control strategies requiring either temporal or locational charge flexibility to meet charging needs while mitigating grid impacts and providing value. DOE could expand activities to develop and demonstrate smart charging ecosystem(s) to implement the SCM strategies consistent with utilities' operational environments, considering deployment within underserved and environmentally sensitive communities. DOE could expand activities to evaluate the round-trip response time and control frequency of the telematic communication pathway. The activity could determine the ability to support SCM and specific grid services at a local level, e.g., load-balancing, demand response or frequency regulation in a workplace environment. DOE could use resources across national labs to provide technical assistance to utilities investigating implementation of SCM to integrate EVs with grid operations. Public funds expended for EVs and EVSE charging infrastructure could consider requiring smart communication capability and open access and/or local control options (i.e., non-proprietary communication) to ensure the opportunity to implement SCM programs. These requirements can be met with an open access charging ecosystem that utilizes standard smart protocols for EV-to-EVSE communication (e.g., ISO 15118-20) as well as open protocols for EVSE-to-energy management system communication (e.g., OCPP 2.0), EMS-to-charging network communication (e.g., OpenADR), and charging network-to-utility/grid operator communication (e.g., OpenADR or OpenFMB). Federally funded EVSE could be network agnostic to avoid stranded assets due to loss of a network provider for business or other reasons. Specifically, the EVSE could be owner-reconfigurable to communicate with a different server/network to maintain its availability and intended functionality to support SCM.
II.D Codes and Standards – Takeaways	The EV ecosystem is facing many challenges with the cross-sectoral and cross-functional nature of standards where standards connect multiple elements of the EV ecosystem (e.g., vehicle-charger,

	charger-charging network operator, and charging network operator-grid). There is a lack of clear delineation of the purviews and conflicting priorities of SSOs, especially between U.S. and international SDOs. EVSE manufacturers, in particular, have a lack of clarity as to which standard they must comply with for their product which creates uncertainty. Comprehensive understanding of the current state of readiness of standards is required and is a prerequisite to identifying needs and requirements and establishing strategies moving forward. Improvements are needed in the standards development processes themselves to better pace technology development throughout the EV ecosystem. There is currently no NTEP testing program for AC or DC EVSE to certify measurement accuracy of electricity dispensed for retail charging. Greater harmonization is required especially with regards to U.S. and international standards. However, harmonization is a difficult goal and efforts are required to articulate its specific benefits and where it would be most appropriate and feasible. The automotive and electric grid standard environments operate on different time cycles and utilize different processes for certification which could result in persistent barriers.
II.D Codes and Standards – Recommendations	DOE could expand activities to convene a forum of stakeholders to jumpstart a process to achieve a unified vision and strategy for codes and standards which identifies and addresses competing standards to remove barriers for SCM and VGI. Stakeholders, with DOE support, could expand activities to work to achieve consensus on high-level requirements for communications, connectivity, interoperability, cybersecurity, resiliency, safety, backward compatibility, future proofing, and metrics. DOE could expand activities to assess the status of codes and standards, test procedures, and supporting technology requirements; identify gaps; and determine priorities for moving forward. DOE could expand activities to strengthen engagement with existing U.S. and international SDOs to enable greater standards harmonization for EV-Grid integration. SDOs could expand participation by consortia of key stakeholders (SSOs such as CharIN) to enhance flexibility and expedite the standards development process. DOE could expand activities to support further development of standards and test procedures for diagnostic interoperability

	testing for VGI, as well as less expensive field-testing equipment for AC and DC charging. DOE could expand activities that, with stakeholder engagement, advance the development of a standard ESI with an open, flexible format. Stakeholders, with DOE Support, could work to identify common diagnostics and data reporting approaches to identify interoperability, communications, or other charging failures proactively to simplify maintenance and improve up-time of EVSE. SDOs could, working with industry partners, require that deployment of new, network connected EV infrastructure have capabilities for over-the-air (OTA) updates where available to patch security gaps, add features/upgrades, and address reliability issues that are uncovered.
II.E Cybersecurity – Takeaways	A lack of cybersecurity has the potential to be a major impediment to the large-scale adoption and integration of EVs with the grid. The vast cross-sectoral nature of the EV ecosystem, combined with the complexity of systems and technologies required to integrate EVs onto the grid, exposes a multitude of cybersecurity vulnerabilities. Cybersecurity must be continually addressed as no EV ecosystem will ever be entirely secure and threats will continually evolve. As communication networks for EVs, EVSE, and external systems increase, the attack surface also increases, leaving the charging infrastructure and wider EV ecosystem more open to exploitation of cybersecurity vulnerabilities. Cybersecurity breaches can affect the operation of the transportation sector by limiting the ability of charging equipment to function, expose personally identifiable and financial information, and more ominously affect safe operations during charging and vehicle operation. A compromised charging infrastructure can pose a major threat to the electric grid. A large-scale synchronized attack can affect large portions of the grid simultaneously. A localized cyber-physical attack can lead to a sudden addition or reduction of load creating voltage imbalances and undesirable power quality impacts resulting in local disruptions such as brownouts, damaged equipment, and market disruptions. A holistic cybersecurity approach will require significantly greater harmonization across many sectors and major advances throughout the portfolio of systems, technology, and tool development. Addressing the cybersecurity challenges will require stakeholder engagement, coordination, and consensus; gap analyses and needs assessments; research and development; and testing, validation, and demonstration.

II.E Cybersecurity – Recommendations	DHS could establish leadership in EV charging cybersecurity by creating a cross-sector Information Sharing and Analysis Center (ISAC) specifically for the EV charging ecosystem. This ISAC could integrate efforts from the Auto-ISAC and E-ISAC. DOE, in collaboration with NIST, DHS, and other Federal agencies, could convene stakeholders to identify key cybersecurity challenges and vulnerabilities to inform the development of a comprehensive cybersecurity roadmap for EV charging and grid integration. DOE could expand activities to work with other Federal agencies and stakeholders to advance cybersecurity education and workforce development for EV charging and grid integration. DOE could expand activities to continue to support stakeholder assessments of codes and standards to identify high priority cybersecurity gaps, needs, requirements, and best practices. DOE could expand activities to undertake activities to increase the awareness of the cybersecurity risk landscape; prioritization of high consequence events and mitigation strategies; and critical technology needs amongst EV grid stakeholders. DOE, in concert with NIST and other Federal agencies, could expand activities to develop strategies for identifying and assessing supply chain cybersecurity vulnerabilities and mitigation strategies for EV charging and grid integration. DOE could expand activities to support SAE and others in the development of a widely accepted PKI for the EV charging ecosystem. DOE could expand RDD&D activities on charging cybersecurity technology solutions to threats on light-, medium-, and heavy-duty vehicle charging and associated risks to the electric grid. These solutions could include identification, protection, detection, response, and recovery. The most promising cybersecurity solutions should be tested, validated, and demonstrated. The Federal Government could support the establishment of cybersecurity testing procedures, platforms, and protocols to strengthen EV charging stakeholders' cybersecurity posture.
II.F Technology Adoption at DOE Facilities - Takeaways	It is feasible to adopt DOE developed SCM and EV-Grid integration solutions at DOE facilities.
II.F Technology Adoption at DOE Facilities - Recommendations	DOE could expand activities to utilize its facilities for the validation and demonstration of SCM and EV-Grid integration solutions developed by the Department.

B. DOE's Vehicle Grid Integration Roadmap

i. Overview

On April 22, 2021, the United States set a goal of decarbonizing the U.S. electric grid by 2035 and creating a net zero emissions U.S. economy by 2050.[156] A significant element of that new future includes the vision of an electrified transportation sector. Moving to large-scale EV adoption in the United States, EVs@Scale will require close coupling with the electricity sector. Bringing the power and transportation sectors together will create greater interdependencies than currently exist, making it imperative that long term strategic issues are proactively evaluated and considered. The sectors will need to consciously plan and adapt – not only in isolation but in the context of each operating together – to maximize national and societal benefits and minimize the risks without compromising the primary mission of each sector. The coupling of these two sectors will require careful and disciplined consideration.

Technologies developed, manufactured, and deployed in the United States will be a central focus in the transition to a carbon-neutral economy powered by electrified transportation. Foresighted and judicious integration of EVs with the electric grid, or VGI, is essential. Here, the goal is to strengthen both the transportation and electricity sectors by leveraging of their interdependencies, while minimizing inherent risks, such as reliability and resilience, as the sectors become more closely linked. It will also be important to avoid unintended consequences such as increasing the need for conventional units or peaker power plants where renewables and bi-directional electric vehicle charging infrastructure could be an alternative. To support the transition to EVs@Scale and overcome challenges to VGI, DOE has established bold goals that support the Department's VGI Vision and Mission and are the basis for the VGI Initiative.

Vision – The VGI Initiative will advance capabilities necessary for the United States to cohesively accomplish transportation electrification, grid modernization, renewable energy resources integration, climate change mitigation and adaptation, enhance energy security and resilience. VGI will ensure equitable access and environmental justice. VGI I will achieve an electrified U.S. transportation sector that is supported by a modernized electric grid that is flexible, reliable, resilient, affordable, and secure, allowing for robust Vehicle Grid Integration that benefits the nation, reduces greenhouse gas emissions, supports strong economic growth, and fair market access.

Mission – DOE, in concert with industry, will conduct RDD&D of systems, technologies, and solutions that propel transportation electrification in the United States forward and develop a strong U.S. manufacturing base. Innovative technologies developed in the United States should be manufactured domestically, establishing the Nation as a world

[156] White House. FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies. April 22, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/ referenced on October 19, 2021.

leader in VGI. These activities will also promote equity and environmental justice by reducing costs and improving access for all stakeholders.

Goal – Facilitate development and harmonization of a robust, interoperable, economically vibrant, resilient, cybersecure EV charging infrastructure that is integrated with a decarbonized modern grid.

ii. Need and Background

EVs represent an increasing fraction of the U.S. transportation fleet and in the future will become a significant load on the electric grid. Successful deployment of EVs@Scale, referred to as upwards of 20 million EVs on the road, will necessitate a robust and secure charging ecosystem and will require a holistic approach that encompasses the vehicle, charging infrastructure, and the electric grid. Figure III.1 presents the key components of transportation electrification ecosystems. This includes controls, interoperability, wireless and other advanced HPC technologies, and integration with the grid and DER such as stationary storage and PV.

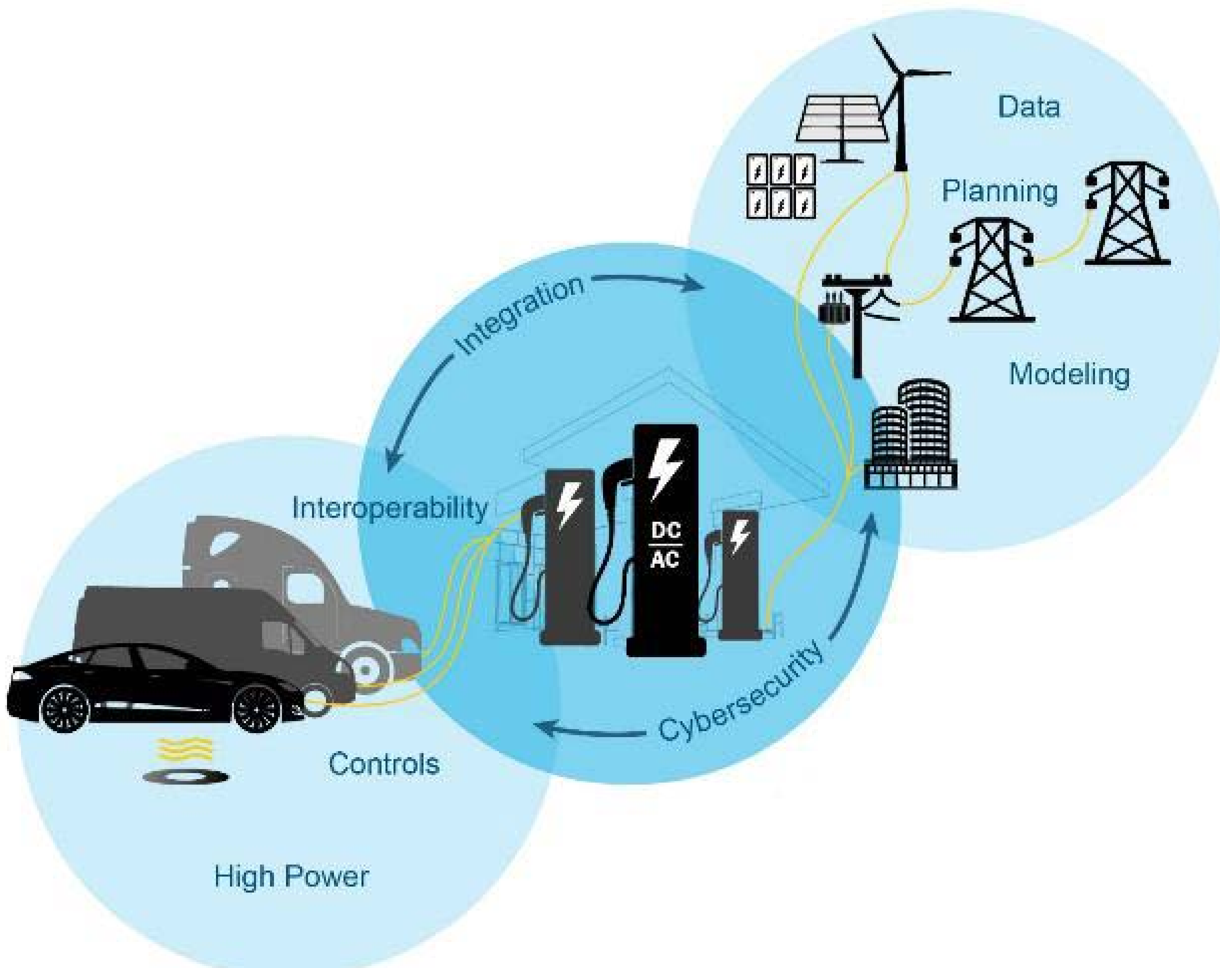


Figure III.70. Key components of transportation electrification ecosystems.

The effective control and optimization of the charging ecosystem is essential and is otherwise known as Smart Charge Management (SCM). SCM is one tool that can help reduce the potential grid impacts of EVs@Scale, while providing enhanced value for EV/charging/grid systems, including reduced costs and increased opportunities for grid services.

As of December 2023, the U.S. Department of Energy Alternative Fuels Data Center estimates there are approximately 64,000 public and private EV charging stations with more than 166,000 charging ports in the United States. This includes approximately 9,000 DC Fast stations with a total of 36,000 charging ports, 56,000 AC L2 stations with a total of 121,000 charging ports, and 228 AC L1 stations with a total of 800 charging ports.

HPC, defined as up to 400 kW for light-duty EVs, and 1+ MW for medium- and heavy-duty EVs, can enable greater vehicle utilization, extend the vehicle range, and reduce recharging times. Technical advances are steadily being made with regards to HPC, but further progress is needed to facilitate the mass market adoption of EVs. Proper siting of HPC is also needed to minimize stress on the energy system. Where grid constraints exist, co-locating HPCs with microgrids could provide a solution as well as additional grid benefits that could be monetized under the right conditions.

The electric power grid needs to provide the power to charge the increasing number of EVs. This includes not only providing the source of the power, but also the mechanisms to safely and efficiently transmit it to the EV. All aspects of the power system (generation, transmission, and distribution) need to work in concert to accommodate the growing EV load. However, distribution-level impacts and behavior will be the most immediately impacted, especially in areas of older infrastructure and/or lower operating voltages. The rapidly evolving deployment of EVs and the varied nature of the distribution power system in the United States make this a very complex problem. Continued development of tools and techniques help to plan for and evaluate these impacts. Expanding existing technologies and creating new operating approaches to integrate EVs and other DERs will help ensure the power system continues to operate efficiently and reliably.

The successful wide-scale implementation of EVs requires simplified, streamlined interaction across the EV ecosystem including robust, comprehensive standards and protocols for EVs, charging systems, and interconnection to the grid. Standards research, development, and demonstration is necessary to enable smart charging, DERs, including EVs, to demonstrate grid services, to enhance local grid resilience, and to establish EV charging microgrids. In short, advances in standards for communications, interconnection, and interoperability, as well as supporting test procedures and certification, are a necessity and will enable further work to harmonize requirements across technology domains, develop widely applicable interfaces, and promote seamless operation across the EV ecosystem.

Cyber related risks and consequences dramatically increase with rapidly increasing numbers of EVs with advanced communication functionalities and networked chargers, as well as the trend towards HPC. A comprehensive understanding of the threat environment, including risks and consequences therein, is needed to identify, minimize, and/or eliminate critical cyber-physical vulnerabilities. Coordinated cyber-attacks on chargers/charging stations can lead to serious local and potentially broader grid disruptions, such as wide-scale blackouts and/or brownouts.

Addressing the barriers above can only be done by conducting high risk projects that are beyond the suitable scope and developmental timeframes of industry. Historically, the transportation and utility sectors have not worked together, complicating collaboration. A significant level of pre-competitive and vendor-neutral R&D effort is needed to address the technical challenges associated with a safe and secure charging ecosystem for EVs@Scale.

In addition to the technical challenges are the market challenges. Figure III.2 illustrates the traditional utility value chain and where electric vehicles could participate to provide benefits to the energy system like other distributed energy resources.

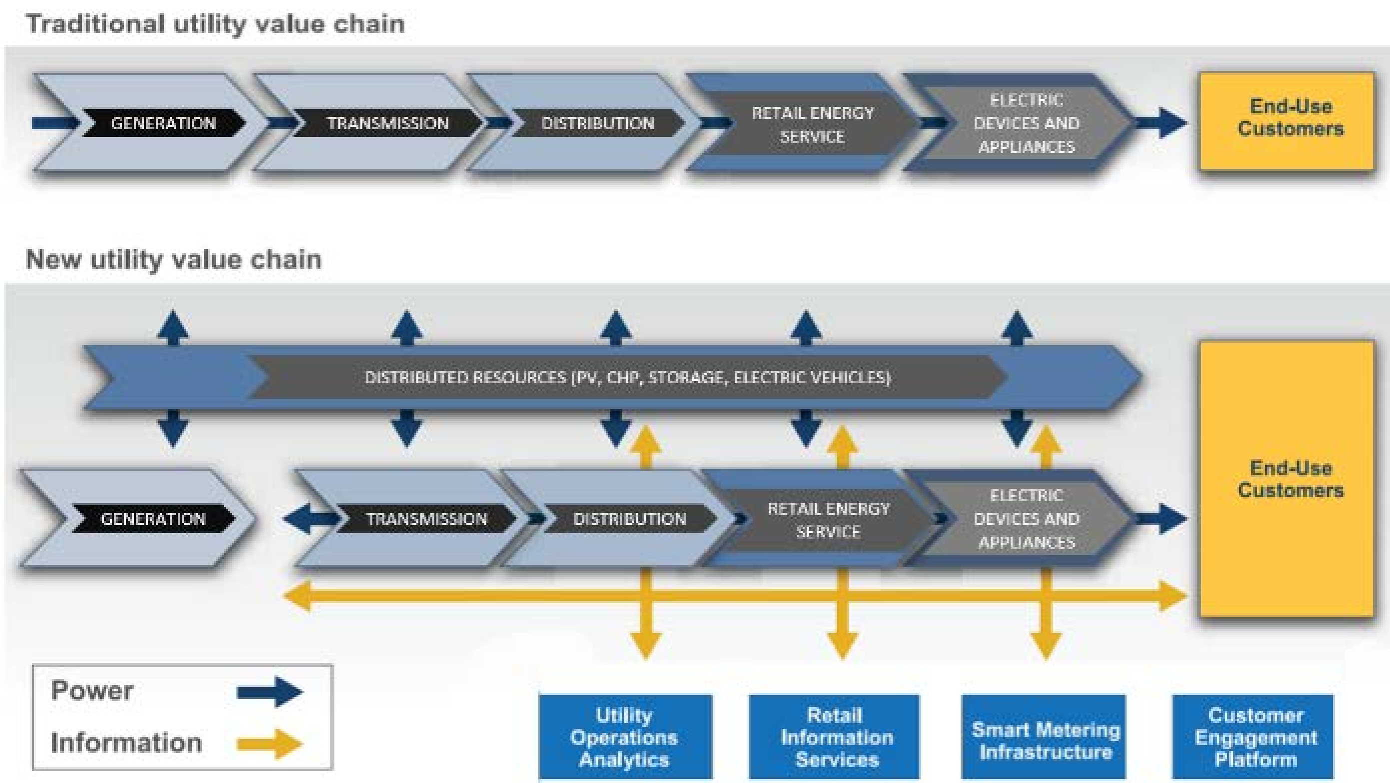


Figure III.71. Transformation of the electric utility value chain[157].

Regulatory barriers exist which will require work and collaboration to help streamline the interconnection process, as well as an evaluation of how EV-Grid services (e.g., peak shaving, leveraging more renewables, or deferring grid upgrades) are assessed for cost, value), and compensation at the distribution level. Fair market access for EV-Grid services as DER is nascent. It is important to note FERC only has jurisdiction over transmission operations, which

[157] Adapted from: NEMA. (2016). Powering Microgrids for the 21st-Century Electrical System. Powering Microgrids for the 21st-Century Electrical System (nema.org). Referenced on 18 October 2021.

include wholesale energy markets. Equivalent energy markets do not exist at the distribution level, so alternative options and new business models need to be evaluated for integrating electric vehicles, which will vary by state and local utility. Alternative options included, but are not limited to, rebates, state or Federal tax credits, tariffs, or transactive energy. Transactive energy could be introduced and demonstrated at the distribution level to incentivize specific types of EV-Grid integration, such as V2G where needed.

iii. DOE's Approach

The goal of the DOE's Vehicle Grid Integration 10-Year Roadmap is to outline a holistic Department-wide strategy, the VGI Initiative, to accelerate adoption of electric vehicles and facilitate vehicle to grid integration in such a way that transportation and energy networks work together as a symbiotic system capable of delivering transport and energy services. This new system could create new value streams while simultaneously alleviating supply chain and grid resilience issues while mitigating challenges associated with integrating intermittent renewable energy generation.

This strategy starts with fundamental research and development for electric vehicle to grid integration technologies following through to demonstration and deployment. The Department will use its resources to conduct RDD&D that other stakeholders are not able to perform and use its convening power to establish U.S. global leadership in EV-Grid integration.

The purpose of fundamental research and development is to identify system pathways and conduct research to facilitate the development and harmonization of robust, interoperable, and cyber-secure electric vehicle charging and grid infrastructure that supports EVs@Scale and incorporates advanced charging technologies, DER, and grid services.

DOE will continue to collaborate with industry, other Federal agencies, state and local governments, regulatory bodies, and organizations (such as standards development organizations) to accelerate the pathway to commercialization for vehicle to grid integration. On an ongoing basis, the Department will work with industry and other stakeholders to apply feedback when developing RDD&D activities, sharing use cases, and identifying existing DOE developed technology that may be commercialized to advance vehicle to grid integration.

To execute the strategy, DOE is launching the VGI Initiative that will include a cross cutting internal VGI task force to facilitate robust communication, coordination, and collaboration within government and industry, which is essential to enabling the transition to EVs@Scale and to achieving successful integration with the grid (see Figure III.3). Within DOE, the EERE VTO; OE; CESER; and OTT, are actively coordinating to advance the integration of EVs with the grid. These efforts will include joint participation on collaboration-appropriate projects, as well as review and input on each Office's projects, lab calls, and solicitations. Through the task force, DOE will work across the appropriate program offices to create a feedback loop to ensure VGI technologies are researched, developed, demonstrated, and have a path to deployment. In addition to these RDD&D activities, the Department's EVGrid Assist effort will provide education and technical support to stakeholders as they adopt EVs and address VGI.

Demonstration projects are intended to show the technical and economic viability and can uncover unforeseen barriers.

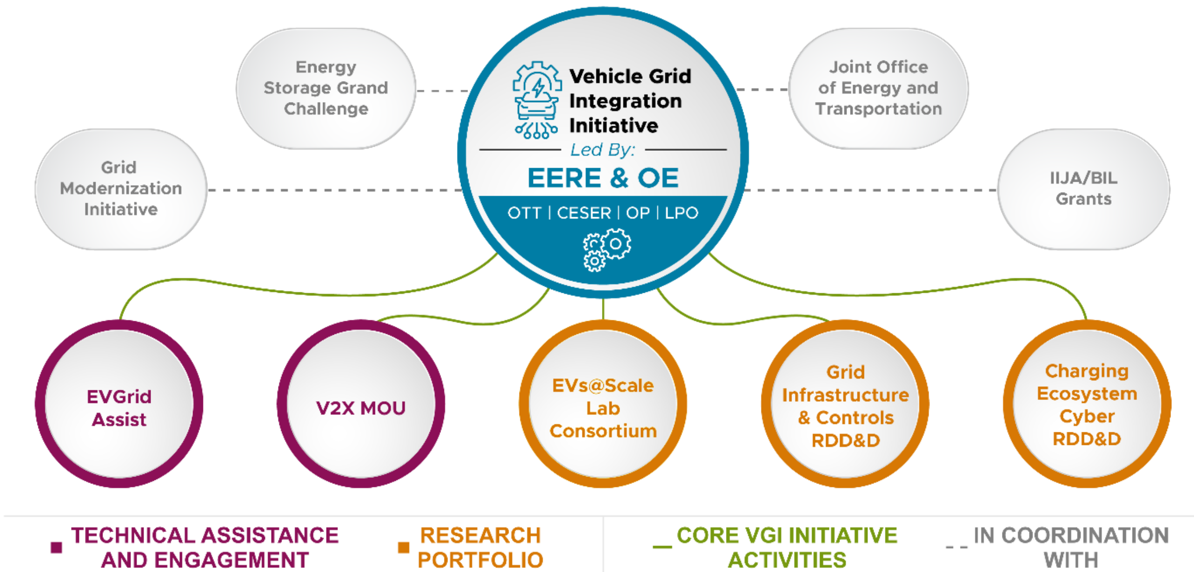


Figure III.72. DOE VGI Initiative Participants and Focus Areas.

DOE coordination extends to many government agencies including NIST, DHS, DOT, and DOD. In addition, DOE has long-standing relationships with industry and the private sector through the U.S. DRIVE GITT and 21st Century Truck Partnership-Electrification Tech Team (21CTP-ETT) Charging Working Group, which will be continued. The Department will establish additional relationships with Federal, state, and local entities as well as the private sector as appropriate to further support DOE's VGI activities.

DOE has also decided that a consortium of National Laboratories should be created to address VGI for EVs@Scale. EVs@Scale will require the buildout of a significant charging infrastructure and corresponding potential upgrades to the distribution grid, which will create new challenges to VGI requiring innovative solutions. The EVs@Scale Lab Consortium will work on these solutions utilizing the unique expertise, capabilities, and facilities of the National Laboratories. The consortium will enable highly coordinated, precompetitive research to be initiated and successfully conducted in a manner that drives innovation and maintains DOE leadership despite the rapid changes in the EV charging ecosystem. The EVs@Scale Lab Consortium will include feedback loop with a diverse, inclusive, and representative set of grid integration stakeholders. By bringing stakeholders in as project participants when appropriate, the transfer of developed technologies, tools, data, and learnings will be accelerated.

DOE RDD&D is focused on EVs, EVSE, and integration with the grid. The emphasis is upon foundational systems analyses; exploratory RDD&D; and cyber-physical security (CPS); especially in critical areas that other stakeholders are not able to address. The five strategic areas addressed by the DOE are SCM, HPC, grid management and control (GMC), codes and standards, and CPS of charging infrastructure, as shown in Figure III.4. Interoperability is needed across all the strategic areas to ensure technically viable deployments.

Each strategic area informs the others, providing a feedback mechanism to continuously refine and adjust RDD&D direction and focus. RDD&D activities span electrification of the light-, medium-, and heavy-duty sectors of transportation. Additionally, given the cross-sectoral nature (vehicle, charging infrastructure, and the electric grid) of these activities, DOE emphasizes close communication and coordination with other governmental and industry stakeholders, including Federal agencies, charger and vehicle OEMs, utilities, and charging network providers.

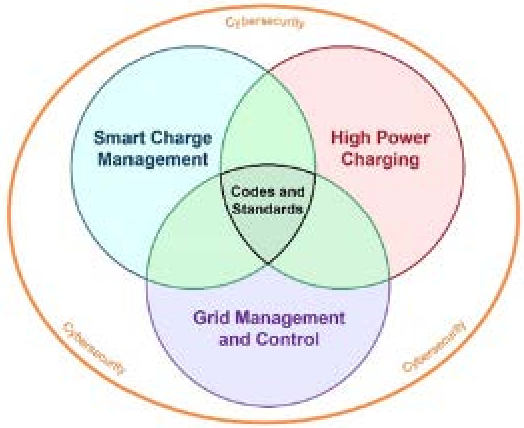


Figure III.73. Strategic areas of the DOE's Grid and Infrastructure RDD&D Activity.

C. Strategic Action Areas

i. Smart Charge Management

Importance

The focus of Smart Charge Management (SCM) is to identify pathways to reduce the potential grid impacts of EVs@Scale, while providing enhanced value for EV/charging/grid systems, including reduced costs and increased opportunities for grid services. If unmanaged, EVs@Scale connecting to the grid would create numerous challenges for utilities, particularly at the distribution level. SCM techniques can be employed to intelligently control, and shift charging loads to mitigate this problem and facilitate the provision of advanced grid services from EV charging.

Adoption rates and fleet sizes of light-duty EVs are significantly higher than medium- and heavy-duty classes. Personal use light-duty EVs have typically very low constraints and hence the highest flexibility for load control, which makes them suitable candidates for SCM. State of the art for SCM includes simple control of charge rates of EVs at residential and workplace chargers based on incentives, rate signals, and time-of-use. These tools provide limited grid services and SCM functionalities. For all EVs, formulation of temporal and spatial flexibility based on applications and dwell times are key and need research. SCM is one of the key building blocks for a successful and seamless grid integration of EVs. Relevant R&D areas in grid integration of EVs@Scale include V2X (Vehicle to Home (V2H), Building (V2B), Grid (V2G), etc.), DCaaS, sensors and measurement, and microgrids/facility designs.

Specific challenges and barriers to SCM include determining the impact of controlled charging versus uncontrolled charging, identifying critical strategies, and enabling, developing, and demonstrating SCM technologies in integrated networks of building systems and DERs, including stationary storage, and facilitating bi-directional power flow. Interoperability and scalability of SCM systems are needed to allow EVs from all OEMs to charge at EVSE from multiple vendors to enable EVs@Scale. High speed communication and controls with compatible device protocols and test tools for verification are required. SCM research is also needed to develop strategies and technologies for charging all EVs to enhance station resilience and mitigate potentially negative grid impacts. Finally, costs should be factored into the design of SCM hardware and grid upgrades so that they are minimized, while still providing the necessary charging service.

DOE R&D Outlook for SCM

Figure IIV.5 illustrates key elements of SCM including predictive charge decision making, controls, and integration of vehicle charging and distributed energy resources with buildings and the grid. Future SCM activities target light-, medium-, and heavy-duty EVs and fleets at charging stations, fleet depots, and travel centers. R&D is needed for real time detection and implementation of mitigation procedures when an EV charging station is acting out of the norm or has suffered a cyber breach. Likewise, for medium- and heavy-duty EV fleet charging at depots and travel centers, the focus is to develop and demonstrate SCM strategies, systems, and tools to provide benefit to medium- and heavy-duty fleets and owners, and to reduce potential grid impacts. To achieve effective SCM, a thorough understanding of HPC charge profiles, both conductive and inductive, is required for optimal integration of charging stations and the utility distribution grid. Another future thrust is to identify viable V2X applications and requirements, and to subsequently develop and demonstrate technologies (on and off board) for low cost, interoperable, controllable, and bi-directional power flow.

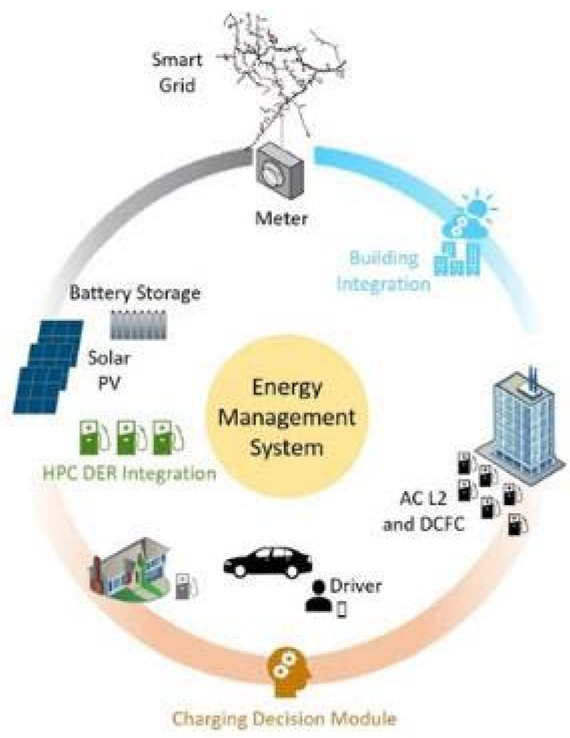


Figure III.74. Key elements of Smart Charge Management.

The following activities are needed to facilitate the timely, cost effective, and secure integration of EV charging with the grid. Some of these activities will require multiple program Offices within DOE to collaborate to achieve the desired goals, including EERE, OE, OTT, and CESER. The relevant Offices will undertake those actions where funding has been appropriated.

- Evaluate and develop grid and transportation scenario criteria to measure the effectiveness of the full diversity of smart charge management options.
- Develop viable smart charge management strategies and relevant tools to reduce the potential grid impacts of EVs@Scale and enhance the value of EV charging systems by enabling grid services.
- Demonstrate and validate smart charge management strategies and relevant tools capable of controlling wide-scale utilization of high-power charging at 400 kW and above, while incorporating robust cyber-physical security methodologies.
- Identify technology and market barriers to grid service use cases then develop and demonstrate solutions for high value use cases.
- Develop a data access and privacy framework that articulates roles, rights, and responsibilities across the variety of data/ownership boundaries.
- Investigate the feasibility of incentives, controls, and market design activities for grid service use cases that consider the consumer behavior and demographics of EV ownership (which will shift away from early adopters).
- Develop frameworks to identify security gaps that can result from the introduction of new SCM technologies or advances in grid integration.
- Identify appropriate energy systems cybersecurity solutions and adapt them to SCM.

ii. High Power Charging

Importance

Successful deployment of High Power Charging (HPC) for light-duty (up to 400 kW) and medium- and heavy-duty (1+ MW) EVs offers numerous benefits, including greater vehicle utilization, extended range, and recharging times comparable to refueling for conventional vehicles. However, current state of the art for HPC systems is at an early stage for light-duty EV charging at 400 kW, and the technology does not currently exist for medium- and heavy-duty charging at 1+ MW. HPC systems face multiple technical challenges and must be intelligently designed and integrated with the grid and DERs to mitigate ramp rates and surge power demands, lower system total cost of ownership, maximize the potential for grid services, and enable interoperability of HPC infrastructure with medium- and heavy-duty EVs.

HPC exploratory R&D and analyses are needed to address issues associated with materials, power electronics, thermal management, and overall costs. Specific barriers exist with thermal loading of equipment and cables that enable service from the medium voltage grid and power transfer to the vehicle. Investigations are also needed into automated EVSE for HPC, especially above 400 kW charging levels. Advances in wireless charging are required, including the development of novel coils, advanced field shaping technologies, and mitigation of stray electric and magnetic fields.

Likewise, assessment and research are needed to understand the impacts of HPC on the grid, and unexpected grid events on HPC-enabled vehicles, and to help determine the appropriate response from EVs and EVSE. Clear understanding of both the impact of large numbers of HPC systems on transmission lines and distribution feeders and of methods to integrate and control stationary storage and other DER, in support of HPC, are needed. HPC should be an R&D topic of forecasting, planning, and co-simulation with grid infrastructure for both long term (years) and short term (seconds to subseconds) intervals. Furthermore, identification and development of control strategies will be required to enable HPC stations to provide grid and building services.

DOE RDD&D Outlook for HPC

Figure III.6 provides a conceptual configuration of an HPC station for medium- and heavy-duty EVs. Future HPC activities target several areas including integration of dynamic wireless power transfer (dWPT) into roadways and development of innovative means to provide service to charging facilities. Deployment of dWPT into the roadway will require researching performance, field emissions, and power and control requirements, and addressing integration of the charging system. DCaaS is an approach to provide DC to charging stations that seamlessly integrates facility and EVSE loads, and DER. Research is needed to address DC isolation, metering, measurement, and protection.

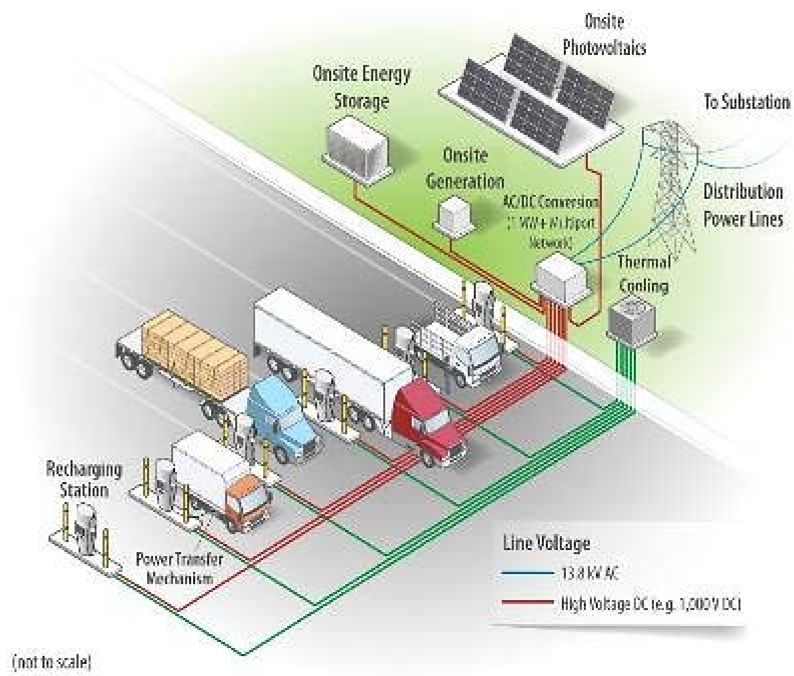


Figure III.75. Conceptual configuration of an HPC station.

The following activities will facilitate the timely, cost effective, and secure integration of EV charging with the grid. Some of these activities will require multiple program Offices within DOE to collaborate to achieve the desired goals, including EERE, OE, OTT, and CESER.

DOE could take the following key actions to facilitate the development and seamless adoption of HPC technologies that reduce the time to charge EVs and the cost of equipment, grid integration, and charging:

- Develop, demonstrate, and validate strategies and technologies for high power dynamic wireless charging and multi-port 1+ MW charging stations that enable vehicle charging through direct connection to medium voltage (≥ 12.47 kV) distribution.

Develop and utilize tools for planning, modeling, and forecasting to anticipate growth of HPC and its impacts on transmission and distribution systems.
Investigate the potential emergence of power quality issues related to high power charging and the possibility of new grid services.
Develop tools for identifying potential HPC sites that could include co-location of microgrids to minimize grid constraints and provide system benefits.

iii. Grid Management and Control

Importance

The grid must adapt to serving a growing population of electric vehicles, in addition to the residential, commercial, and industrial loads that it serves today. EVs are unique in their ability to move, and in the magnitude of power flow and the optimum duration in which to provide it. Because the electric grid is a vast network of lines connecting generation points and load points, the grid can solve problems with network and local capabilities. Additionally, adaptations to new opportunities like transportation electrification occur on multiple timescales, simplified into “planning” (decades to years) and “operational” (years to seconds) time horizons. As a result, research and development in this domain seeks solutions across the full breadth of the way the grid is managed and operated.

Distribution planning needs to evolve to accommodate a more rapid pace of change, the elevated importance of distribution control for grid stability, as well as higher levels of uncertainty. Grid planning generally looks at a minimum of 5 years ahead, out to 40 years in some cases. Additionally, distribution system planning and transmission system planning are historically separate from each other. Because of the rate of change of transportation electrification has the potential to be very high, and the electric system is already transforming because of decarbonization and distributed energy solutions, converged or complementary planning processes may be needed. EVs, DER, and decarbonization also introduce higher uncertainty into the planning process, which creates challenges for large scale public investment in a regulated environment.

A common area of research to both long- and short-time horizons is modeling and forecasting. Planning is best pursued in tandem with simulation and modeling, to aid decision makers in considering thousands of variables and dozens of alternatives. The same is true in operational environments, where implications of decisions must be evaluated across seasons and a diversity of both good and bad events that are best explored virtually. Areas of interest include incorporation of transit networks and charging infrastructure evolution, influence of behavior or incentive response, and transient and harmonics effects of chargers (especially XFC and wireless charging), groups of chargers, or regionally distributed chargers.

As stated previously, electric vehicles are not the only revolution impacting the grid, and the combined influence of decarbonization, DER, and EVs require that these trends not be evaluated in isolation. All three also affect both transmission and distribution, making for challenging research topics. In some cases, optimizations between DERs (including storage, generation, flexible assets) and EVs can occur “behind the meter”, where the grid is not directly involved. In other cases, however, the grid can be a more active participant, involving R&D on "nodal" solutions such as grid-side storage or solid-state transformers and "network" solutions such as synchronizing generation locally or regionally, or absorbing disturbances at multiple spatial scales.

DOE R&D Outlook for Grid Management and Control

Because the potential electric vehicle impacts on the electric grid over a 10-year horizon are highly varied, the state of readiness of the full diversity of distribution and transmission system networks in the United States should be assessed. Part of this undertaking should be in the form of a Sector Coupling Analysis, beginning with an architectural framing of the electric and transportation sectors, and proceeding through macro-level simulation and modeling. In parallel, a greater awareness is needed of distribution system topologies, voltages, and other characteristics in use in the country today, such that specific research advances can be adapted to suit the specific needs of regions, states, and localities.

The following activities will facilitate the timely, cost effective, and secure integration of EV charging with the grid. Some of these activities will require multiple program Offices within DOE to collaborate to achieve the desired goals, including EERE, OE, OTT, and CESER.

The following activities could be pursued with this foundation established.

- Develop and utilize co-simulation and modeling capabilities to ensure that EVs@Scale can be assessed within a multi-influence environment, such as distributed solar, storage, smart buildings, and high resilience architectures. Simulation tools and models should be capable of both engineering and economic analyses suitable for informing electric utility, regulatory, and other stakeholders.
- Advance the state of the art in simulation and modeling to ensure they accurately represent grid disturbance events related to transients and harmonics due to the behavior of chargers, groups of chargers, and regionally distributed chargers.
- Investigate the potential emergence of power quality issues related to HPC and the possibility of new grid services.
- Evaluate at what penetration levels of DER, including EVs, will create a tipping point where utilities will need the sophistication for managing charging and V2G operations.
- Ensure that current aggregator and other third-party grid participant business and operational definitions in the regulation space allow participation by new entrants such as EV-only aggregators and EV and EVSE manufacturers.
- Evaluate and demonstrate the value of new VGI business and operational models to identify potential cost reductions and facilitate market access.
- In addition to the emerging need for joint planning activities between transmission and distribution operations, planning tools need to support decision making under higher uncertainty, both in terms of forecasting of potential EV load as well as system dynamics.

iv. Codes and Standards

Importance

The successful wide-scale implementation of EVs requires simplified, streamlined interaction across the EV ecosystem including robust, comprehensive standards and protocols for EVs, charging systems, and interconnection to the grid. Standards research, development, and demonstration is necessary to enable smart charging, DER including EVs to demonstrate grid services, to enhance local grid resilience, and to establish EV charging microgrids. Standards are required to enable networked communications and energy management systems to interface with multiple devices and communications protocols and control strategies for charging equipment (individual or aggregated) to communicate with the grid. However, it is important to note that standards and protocols alone are not entirely sufficient as they do not cover the full end-to-end communication requirements. In short, advances in standards for communications, interconnection, and interoperability, as well as supporting test procedures and certification, are a necessity and will enable further work to harmonize requirements across technology domains, develop widely applicable interfaces, and promote seamless operation across the EV ecosystem.

The EV ecosystem is facing many challenges with regards to codes and standards. This includes the cross-sectoral and cross-functional nature of standards where standards connect multiple elements of the EV ecosystem (e.g., vehicle-charger, charger-charging network operator, and charging network operator-grid). Figure III.7 provides sense of the standards relevant to this space and how they overlap across the different components of the EV charging value chain. One standard often serves more than one function: for example, communications and cybersecurity or electrical requirements and safety. Given the breadth of standards activity, another challenge is comprehensively understanding the current state of readiness, which is a prerequisite to identifying needs and requirements and establishing strategies for moving forward. Improvements are needed in the standards development processes themselves to better pace technology development throughout the EV ecosystem and greater harmonization is also required – especially with regards to U.S. and international standards.

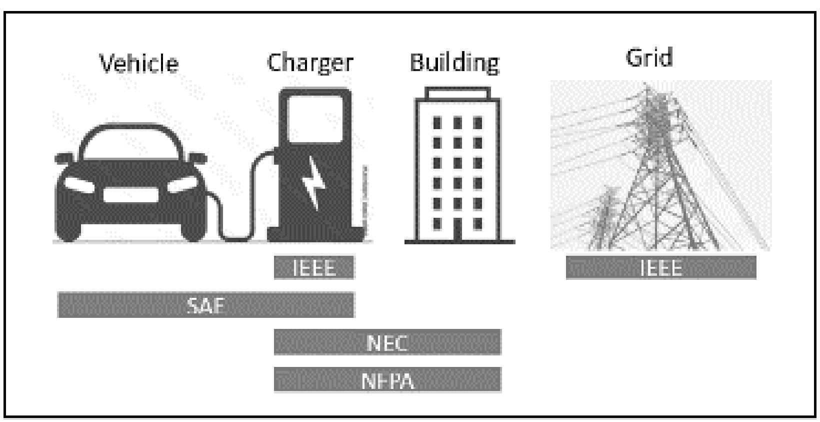


Figure III.76. Relationships of standards across equipment.

DOE R&D Outlook for Key Focus Areas

As a result of the challenges to codes and standards development for the EV ecosystem, there are several needs that can be broadly categorized to include stakeholder engagement, coordination, and consensus; establishment of requirements; enhanced standards development processes, and implementation. The need for strong, committed leadership and a clear vision is essential due to the vast, cross-sectoral nature of standards, especially recognizing that standards are also cross-functional and inter-relational. After the development of a unified vision and strategy, a first order priority is the establishment of high-level requirements for a broad range of codes and standards elements including communications, connectivity, interoperability, safety, cybersecurity, resiliency, backward compatibility, future proofing, and metrics. Data driven, open, and functional standards to facilitate interoperability across interfaces and harmonization across domains are essential. A comprehensive review and assessment of the state of readiness of codes and standards, test procedures, and supporting technology requirements is needed.

Historically, the three key elements of the EV ecosystem – vehicles, charging infrastructure, and grid – have not been tightly coupled, resulting in SDOs creating standards without interconnection and harmonization. There are several key elements that may serve to enhance the standards development processes including: greater government-industry leadership and coordination, increased U.S. participation in international standards development, staying abreast of potential regulatory issues, further participation of non-SDOs in the standards development process, adoption of standards by reference, and independent piloting and testing. EVs should be able to plug in and charge anywhere, be interoperable, and at a minimum implement basic functionality. To support these requirements, advances in codes and standards and subsequent implementation is needed for the EV ecosystem. For example, effective, widescale implementation of smart charge management requires establishment of uniform practices in coordination with supporting codes and standards. Furthermore, challenges facing mega-watt level multiport charging facilities are extensive and uniform codes and standards are required for effective and safe operation. The supply chain is another critical area that requires increased attention from a codes and standards perspective, as well as more consistency and harmonization of state codes.

The following activities will facilitate the timely, cost effective, and secure integration of EV charging with the grid. Some of these activities will require multiple program Offices within DOE to collaborate to achieve the desired goals, including EERE, OE, OTT, and CESER.

DOE could take the following key actions to advance codes and standards to enable smoother operation across the EV charging ecosystem:

- DOE could convene a forum of stakeholders to jumpstart a process to achieve a unified vision and strategy for codes and standards which identifies and addresses competing standards to remove barriers for smart charge management and vehicle grid-integration.

- DOE could support stakeholders to achieve consensus on high-level requirements for communications, connectivity, interoperability, cybersecurity, resiliency, safety, backward compatibility, future proofing, and metrics.
- DOE could assess the status of codes and standards, test procedures, and supporting technology requirements; identify gaps; and determine priorities for moving forward.
- DOE could strengthen engagement with existing U.S. and international standards development organizations to enable greater standards harmonization for EV-Grid integration.
- DOE could support development of standards and test procedures for diagnostic interoperability testing for VGI, as well as less expensive field-testing equipment for AC and DC charging.
- DOE could, with stakeholder engagement, advance the development of a standard ESI with an open, flexible format.

v. Cyber-Physical Security

Importance

EVs and their connectivity with external systems have become increasingly complex. Apart from AC Level 1 chargers, EVSE have evolved rapidly to be networked and maintain a wide variety of communication functions. As communication networks for EVs, EVSE, and external systems increase, attack vectors and cyber-physical risks also increase for the charging infrastructure. Since EVSE at workplaces and public charging stations connect with many different EVs to provide charging services, it makes assuring cyber-physical security (CPS) extremely difficult.

A major challenge posed by compromised charging infrastructure is the threat it poses to the electric grid. A localized cyber-physical attack on a set of EVSE/charging stations can lead to a sudden addition or reduction of loads that can cause local disruptions, brownouts, voltage imbalances, and undesirable power quality impacts. Large-scale, coordinated cyber-physical attacks on charging infrastructure supporting EVs@Scale can also lead to wider grid disruptions, such as blackouts over large geographical areas. The lack of a comprehensive understanding of threats; disjointed implementation approaches; and limited best practices are major barriers to ensuring overall security of EVs, charging infrastructure, and the grid.

The CPS posture of charging equipment, facilities, and management systems being deployed varies significantly based on design and architecture. Additionally, the state of charging operation alters this posture continuously. A wide array of cyber-physical vulnerabilities and risks exist in commercially available EVSE and deployed charging stations. These vulnerabilities result from poor risk management, product implementation, and understanding of risks, as well as a lack of CPS standards and requirements. Improving the overall CPS of charging systems is a shared responsibility across government and industry. Physical vulnerabilities can include insufficient measures to deter and identify intrusions, such as failure to log or generate an alarm when internal compartments are breached and easy access to unnecessary services and ports. Improving the overall CPS of charging systems is a shared responsibility across government and industry and will include investigations of not only the digital attack vectors but deliberate engineering efforts to mitigate vulnerabilities from digital control.

DOE R&D Outlook for Key Focus Areas

Based on the assessments of risk and high consequence events, future activities will implement the best approaches to mitigate vulnerabilities and threats associated with the EV charging ecosystem. This effort will incorporate strategies, systems, and tools for secure charging, including hardware/software for cyber-physical intrusion detection, threat mitigation and isolation, and recovery. The most promising CPS countermeasures will be identified based on risk formulation (e.g., public key infrastructure, block chain, moving target defense, and redundancy). Identified countermeasures that address the highest consequence events will be demonstrated and validated.

The following activities will facilitate the timely, cost effective, and secure integration of EV charging with the grid. Some of these activities will require multiple program Offices within DOE to collaborate to achieve the desired goals, including EERE, OE, OTT, and CESER.

DOE could take the following key actions to improve the cyber-physical security posture of the EV charging ecosystem:

- In collaboration with NIST, DHS, and other Federal agencies, convene stakeholders to identify key cybersecurity challenges and vulnerabilities to inform the development of a comprehensive cybersecurity roadmap for EV charging and grid integration and to identify high priority cybersecurity gaps, requirements, and best practices.
- Work with other Federal agencies and stakeholders to advance cybersecurity education and workforce development for EV charging and grid integration.
- Undertake activities to increase the awareness of the cybersecurity risk landscape; prioritization of high consequence events and mitigation strategies; and critical technology needs amongst EV grid stakeholders.
- In concert with NIST, and other Federal agencies, develop strategies for identifying and assessing supply chain cybersecurity vulnerabilities and mitigation strategies for EV charging and grid integration.
- Support SDOs such as SAE in developing cybersecurity standards, including a widely accepted standard for PKI of the EV charging ecosystem.
- Expand RDD&D activities on charging cybersecurity technology solutions to threats on light-, medium-, and heavy-duty vehicle charging and associated risks to the electric grid. These solutions should include identification, protection, detection, response, and recovery. The most promising cybersecurity solutions should be tested, validated, and demonstrated.
- Assist in the establishment of cybersecurity testing procedures, platforms, and protocols to strengthen EV charging stakeholders' cybersecurity posture. Develop a comprehensive threat model, prioritize high consequence events, and identify appropriate defense, detection, and mitigation strategies and tools for the EV charging ecosystem.

- Continue to support stakeholder assessments of codes and standards to identify high priority cybersecurity gaps, needs, requirements, and best practices.
- Conduct wide-scale demonstrations to validate viable and robust cyber-physical security for the charging ecosystem in support of EVs@Scale.
- Investigate cybersecurity issues associated with the integration of advanced digital controls with legacy utility systems.

D. Summary

DOE is working to address the needs and challenges facing the deployment of EVs@Scale, including smart charge management, high power charging, grid management and control, codes and standards, and cyber-physical security. Each of these five strategic areas are closely integrated and interconnected, some of which require cross-office coordination within DOE. Critical areas of emphasis include interfaces between EV/charging systems/grid, and advanced technologies beyond the scope or developmental timeframes of industry. In coordination with stakeholders, DOE will continue to advance the technological and economic viability, safety, and cyber-physical security of charging EVs@Scale while minimizing potential negative grid impacts and maximizing opportunities for grid services.

IV. Stakeholder Consultations

Offices across DOE (namely VTO within EERE, the Advanced Grid Research & Development (AGR&D) division within OE, CESER, and OTT) routinely engage with stakeholders to understand and assess technology needs and gaps and to identify areas where Federal Government funding can help to accelerate technology development and to remove barriers so that technological advances meet the needs of the nation. DOE also recognizes the importance of bringing stakeholders together to share lessons learned, insights, and successful approaches so that Federal research and funding can be further leveraged for the benefit of the nation.

The transition to electrified transportation and the integration of these vehicles with the electric grid will have implications for a wide range of stakeholders and this broad ecosystem of stakeholders will be critical for implementation. Each has unique needs, requirements, constraints, and considerations. Understanding the challenges and opportunities in a holistic manner requires input from the full ecosystem of stakeholders.

DOE's considerable stakeholder engagement related specifically to EV technology development and integration of these technologies with the electric grid contributed to the development of this report and the 10-year program plan. Stakeholder categories are shown in Table IV.1. . Approaches ranged from individual conversations with stakeholders to gather their insights to formal organizations working to tackle a particular technical challenge to multi-stakeholder initiatives that bridged perspectives. Input gathered through the various stakeholder consultations were integrated into this report.

Table IV.6. Stakeholder groups.

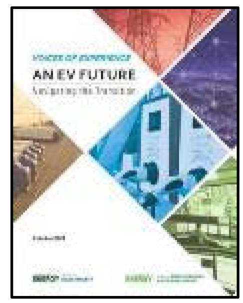
Stakeholder Categories
Academia
Advocates(Environmental Justice, Disadvantaged Communities, etc.)
Aggregators
Charging infrastructure installers
Charging service provider
DER supporting companies (Solar, Controller, Storage, Electric equipment)
Electric utilities
Electric vehicle manufacturers (OEMs)
Electric vehicle supply equipment (EVSE) manufacturers
Energy Companies
Fleet Owners
Government agencies (Federal)
Government agencies (State, Local)
Hardware/Software Vendors
Insurance Companies
ISO/RTO
Private Citizens
Public utility commissions
Retail Fueling (Wawa, Shell, Travel Center)
Trade Associations
DOE National Laboratories
Vehicle battery manufacturers

This section highlights the extensive stakeholder engagements that DOE was involved with or led including ongoing activities. Among, the different approaches used were open forums, industry-government partnerships, collaborative activities, and intergovernmental coordination. These methods of engagement allow for multiple interactions with several of the stakeholder categories. These interactions informed the development of the RDD&D program for integrating EVs onto the electric grid.

A. Open Forums

Open forums provide a means for all people interested in the topic to participate. The open forum approach was used to get broad stakeholder input on different areas of electrified transportation. This report draws on numerous DOE-led open forum opportunities, including "An EV Future: Navigating the Transition", two RFIs, and a webinar series "Is There a Business Case for Bidirectional Electric Vehicles and charging Infrastructure".

i. An EV Future: Navigating the Transition (a Voices of Experience Initiative)



The EV Future initiative, led by OE in collaboration with VTO, convened stakeholders in peer-to-peer conversations related to the build-out of the EV charging infrastructure and its integration with the electric grid. The effort facilitated forward-looking discussions with the numerous stakeholders from across the transportation electrification ecosystem, including electric utilities, state and local governments, OEMs, vendors, charging network providers, advocates, fleet operators, and transit authorities. The objectives of this effort were to explore what the transition to EVs will mean from different stakeholder perspectives. The specific objectives were: 1. To understand the opportunities, potential pitfalls, and considerations for building the necessary electricity and charging infrastructure, 2. To provide a consolidated overview of ongoing activities, and 3. To identify pre-competitive research needs or areas where the Federal Government's expertise, resources, or convening power could assist efforts.

Adapting to changing dynamics related to COVID-19, DOE hosted 33 two-hour virtual workshops over a 10-month timeframe. Topics discussed ranged from economic feasibility to load management to deploying the infrastructure. Table IV.2 shows the full list of topics covered. The workshops allowed participants an opportunity to share their knowledge, experience, and insights. Participation from stakeholders was high, attracting 700 distinct organizations and more than 3,500 registrants. Figure IV.1 shows the number of registrations for each topic workshop. Additionally, the effort was successful in engaging a wide range of U.S. and international stakeholder groups (shown in Figure IV.2 through Figure IV.4).[158] The report, *An EV Future: Navigating the Transition*, captures the information collected through the discussions and can be downloaded at https://www.smartgrid.gov/voices_of_experience.html.

Table IV.7. Workshop Topics for An EV Future: Navigating the Transition.

[158] Figures are based on the registration information collected for each of the workshops.

Planning Conversation	Operations Conversation	Business Conversation
Forecasting	Managing Load	Designing the Infrastructure
Service Requests	New Technology Implications	Deploying the Infrastructure
Understanding Future Requirements	Resilience & Reliability	Economic Feasibility
Deeper Dive Conversations		**Utility-Specific Conversations**
Multi-family and Underserved Communities	Long Haul Fleets and Travel Centers	Lessons Learned from Pilots
Conventional Retail Fueling	Regional and Local Fleets	Programs and Processes

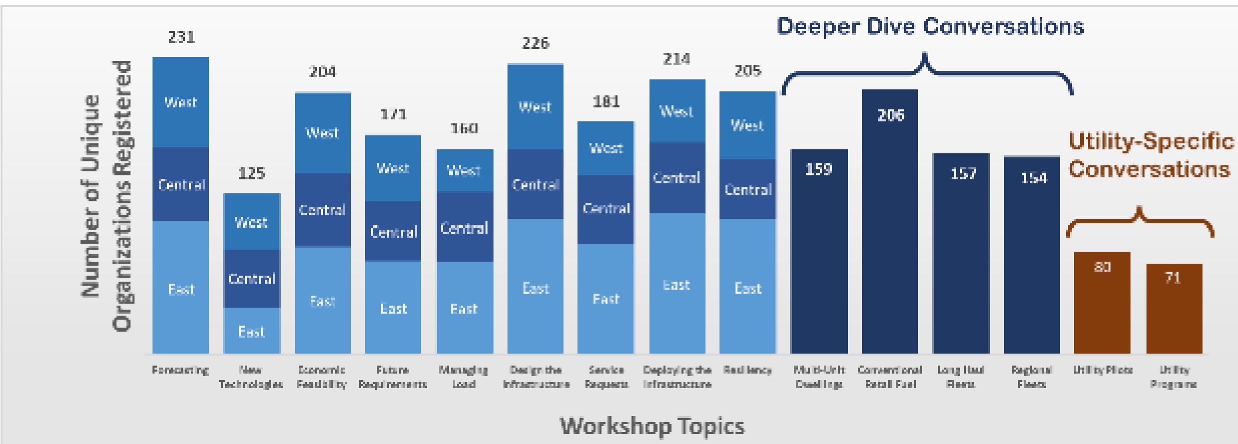
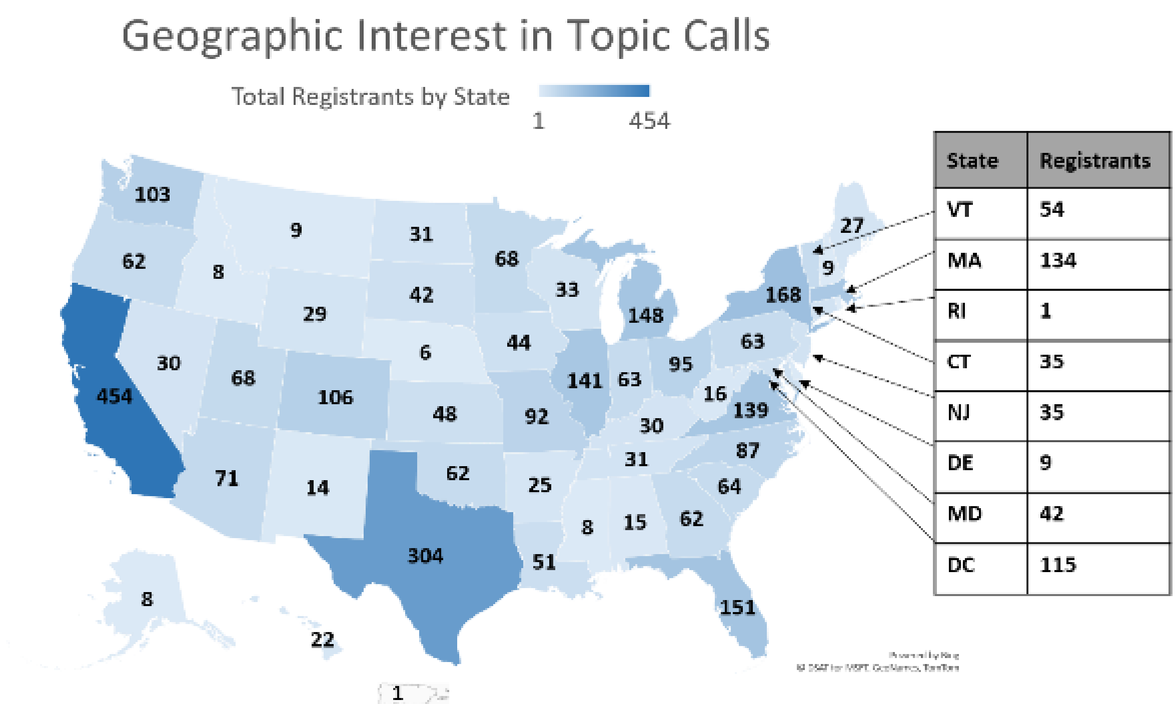


Figure IV.77. Number of organizations registered for each of the Voices of Experience topic workshops.

Figure IV.78. Location of international organizations registered for the Voices of Experience topic workshops.



State	Registrants
VT	54
MA	134
RI	1
CT	35
NJ	35
DE	9
MD	42
DC	115

Figure IV.79. Geographic location of U.S. registrants to the Voices of Experience topic workshops.

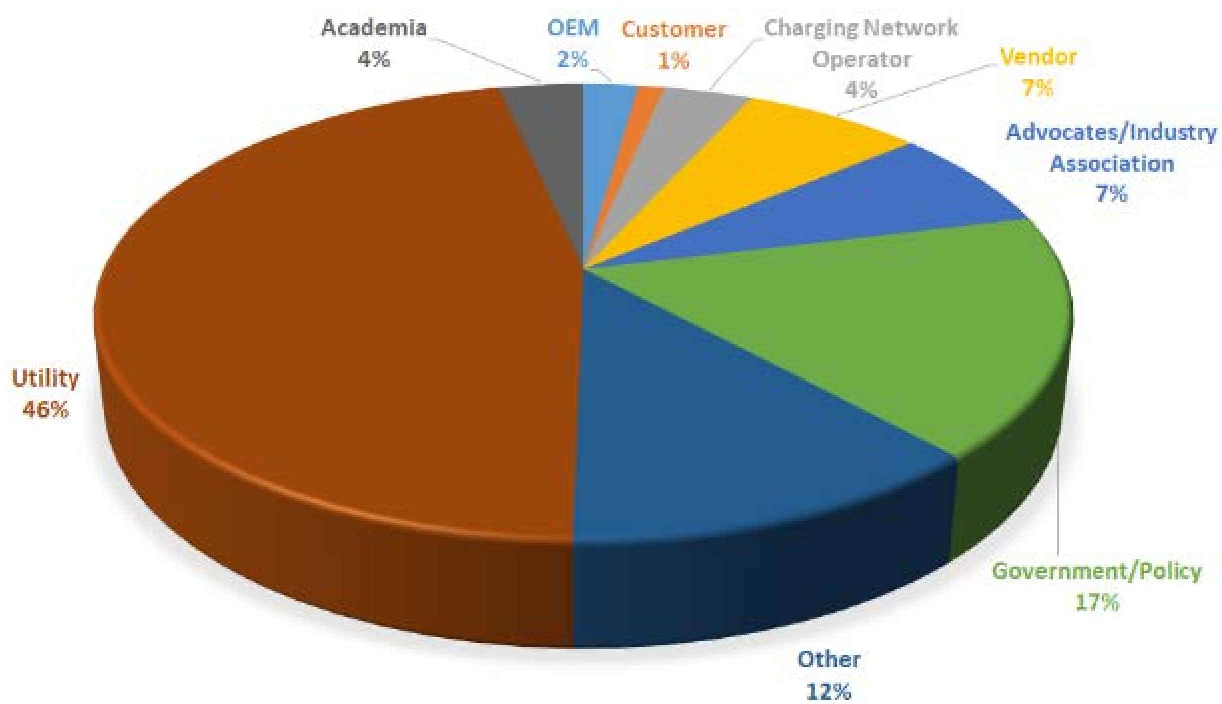


Figure IV.80. Stakeholder participation by category in the Voices of Experience engagement.

ii. Request for Information on Integrating Electric Vehicles onto the Electric Grid

The RFI, released as DE-FOA-0002528, was developed and evaluated by DOE to solicit specific input from industry. DOE received 85 responses with information covering the VGI topics discussed in this report. To gather input from the widest number and variety of stakeholder perspectives, the RFI was posted in the Federal Register, on EERE Funding Opportunity Exchange, and sent to listservs (e.g., sent to EV Future participants/registrants/stakeholder lists).

iii. Request for Information on Energy Storage Grand Challenge

An (RFI) for the Energy Storage Grand Challenge (ESGC), which included bi-directional EVs as mobile storage, was led by OTT in collaboration with EERE and OE. The purpose of the RFI, released in the Federal Register as 85 FR 43223, was to solicit feedback from stakeholders, such as industry, academia, research laboratories, government agencies, and others to assist the ESGC with identifying market opportunities and challenges—both technical and financial—for the development, commercialization, production, and deployment of energy storage technologies. DOE received 187 submissions. Relevant information on V2X and storage technologies from the RFI responses were incorporated into this report.

iv. Webinar Series: Is There a Business Case for Bidirectional Electric Vehicles and Charging Infrastructure?

The Webinar Series: Is There a Business Case For Bidirectional Electric Vehicles and Charging Infrastructure, led by OTT with support from VTO and ANL, convened stakeholders in a series of public panel discussions. The panels described "what bidirectional vehicles are", their capabilities, and potential concerns for the grid if measures are not taken to support adoption of EVs. Light-, medium-, and heavy-duty EVs were explored as potential assets to the grid if they were bi-directional and integrated properly. At a high level, the panels discussed innovative new business models that integrate energy and transportation as a single, dynamic, symbiotic system. One of the panels also discussed how bi-directional vehicles could be integrated into the grid, the technologies involved, and where it's already happening. The panels also discussed how V2X could support reliability and resilience to the grid and offer new revenue streams while supporting smart grid investments.

Over 500 people registered for the two-day webinar and over 300 attended. Panelists and attendees included private and public utilities, independent system operators (ISOs) and regional transmission organizations (RTOs), EV charging companies, EV battery manufacturers, vehicle OEMs, fleet operators, aggregators, state and local governments, etc.

B. Industry-Government Partnerships and Collaborations

Industry-government partnerships are formalized agreements, allowing each party to draw on their unique strengths, to pursue key opportunities for collaborative action to accelerate innovative electric transportation research, development, demonstration, and deployment. Industry-government collaboration benefits from diverse perspectives and unequivocal technical expertise. By bringing government and industry together, DOE can lead the Nation forward and further advance innovation and commercialization. This report draws on numerous partnerships, including U.S. DRIVE, a Memorandum of Understanding (MOU) with EPRI, and 21CTP. Information received from discussions by these partnerships regarding VGI has been included in this report.

Collaborative activities are conducted by a focused subset of partners. These activities have finite scope and definitive conclusions or results. The Summary Report on EVs at Scale and the U.S. Electric Power System 2019, developed by expert team members of U.S. DRIVE, is an example result from collaborative activities. This report draws on numerous collaborative activities, including GITT, ISATT, and CharIN.

i. U.S. DRIVE

U.S. DRIVE, which stands for United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability, is a government-industry partnership among the U.S. Department of Energy; USCAR, representing Stellantis, Ford Motor Company, and General Motors; five energy companies – BP America, Chevron Corporation, ExxonMobil Corporation, Phillips 66 Company, and Shell Oil Products US; four utilities – American Electric Power, DTE Energy, Duke Energy, and Southern California Edison; and EPRI. It is a non-binding and voluntary government-industry partnership focused on advanced automotive and related energy infrastructure technology R&D. The U.S. DRIVE mission is to accelerate the development of pre-competitive and innovative technologies to enable a full range of affordable and clean advanced light-duty vehicles, as well as related energy infrastructure. The partnership focuses exclusively on technologies for cars and light trucks. U.S. DRIVE provides a forum for pre-competitive technical information exchange among partners to discuss R&D needs, develop joint goals and technology roadmaps, and evaluate R&D progress for a broad range of technical areas.

Grid Integration Tech Team

While U.S. DRIVE, the industry-government partnership described above, does not conduct or fund R&D, technical teams (“tech teams”) are the core of the Partnership, bringing together partners’ top scientists and engineers in key focus areas. Tech teams identify technology gaps, develop R&D targets, develop roadmaps to achieve technical targets and goals, and evaluate technical status and R&D progress. Each team has a unique set of objectives, technical issues, position on the research-development-deployment continuum, and relation to industry and government needs. GITT is one of the U.S. DRIVE tech teams.

The mission of the GITT is to support a transition scenario to large scale grid-connected vehicle charging with transformational technology, proof of concept and information dissemination. The GITT facilitates technical coordination and collaboration between vehicle-grid connectivity and communication activities among U.S. DRIVE government and industry partners. GITT addresses enablers for connectivity between light-duty plug-in vehicles, the charging infrastructure, and the electric power grid, encompassing the following:

- Harmonization of Global Connectivity Standards
- Enabling Technology Development
- Enhanced Viability of Fast/Consumer-Friendly Charging
- Managed Vehicle Charging Loads Consistent with Smart Grid
- Reduced Cost of Electric Charging Infrastructure

Integrated Systems Analysis Tech Team

While U.S. DRIVE, the industry-government partnership described above, does not conduct or fund R&D, tech teams are the core of the partnership, bringing together partners' top scientists and engineers in key focus areas. Tech teams identify technology gaps, develop R&D targets, develop roadmaps to achieve technical targets and goals, and evaluate technical status and R&D progress. Each team has a unique set of objectives, technical issues, position on the research-development-deployment continuum, and relation to industry and government needs. ISATT is one of the U.S. DRIVE tech teams.

The mission of the ISATT is to leverage the life cycle and systems analysis core competency within the U.S. DRIVE partnership to generate analysis/knowledge and provide insights for decision-making within the Partnership member organizations. ISATT's primary area of activity is the assessment current and future vehicle-fuel technology options when integrated systems analysis is required. ISATT also undertakes specific topical analyses to examine tradeoffs and synergies related to light-duty transportation and relevant energy systems. Some of the research projects addressed by ISATT are:

- Life cycle assessments for future new mobility scenario analysis
- EV analysis and upstream analysis of movement towards renewable energy, battery second-use, vehicles for load management, electro-fuels, etc.
- Analysis harmonization study
- Vehicle modeling harmonization study
- Target-setting

ii. EERE-EPRI MOU on Electric Transportation

The purpose of this Memorandum of Understanding (MOU) is to allow EERE and EPRI, drawing on their unique strengths, to pursue key opportunities for collaborative action to accelerate innovative electric transportation research, development, demonstration, and deployment. The collaboration facilitates dialogue and coordinates actions to leverage EERE's expertise in transportation energy technology systems through national laboratory capabilities, industry collaborations, and EPRI's research and development on EV and infrastructure technologies and their intersection with the electric utility industry.

iii. 21st Century Truck Partnership

The 21st Century Truck Partnership℠ is addressing important national challenges related to medium-duty and heavy-duty truck efficiency, safety, and emissions by pursuing collaborative research and development among government and industry partners. The partnership is focused on addressing the technical needs of the medium- and heavy-duty truck industry, as well as major policy goals for government agencies. It achieves its goals through focused R&D efforts on topics of broad interest, accelerated technology development through collaborative, pre-regulatory, and pre-competitive R&D component and system-level projects and information exchange and dissemination. The industry, government, and laboratory partners are listed in Table IV.3.

Table IV.8. 21st Century Truck Partners.

Industry Partners	Federal Government Partners	National Laboratories
• Allison Transmission Inc. • Cummins Inc. • Daimler Trucks North America LLC • Eaton Corporation • Ford Motor Company • General Motors Company • Meritor, Inc. • Navistar, Inc. • Oshkosh Corporation • PACCAR Inc. • Stellantis N.V. • Volvo Trucks North America	• U.S. Department of Energy (DOE) • U.S. Department of Defense (DOD) • U.S. Department of Transportation (DOT) • U.S. Environmental Protection Agency (EPA)	• Argonne National Laboratory (ANL) • Brookhaven National Laboratory (BNL) • Idaho National Laboratory (INL) • Lawrence Berkeley National Laboratory (LBNL) • Lawrence Livermore National Laboratory (LLNL) • Los Alamos National Laboratory (LANL) • National Renewable Energy Laboratory (NREL) • Oak Ridge National Laboratory (ORNL) • Pacific Northwest National Laboratory (PNNL) • Sandia National Laboratories (SNL)

iv. CharIN

CharIN is an industry consortium. It is a non-profit organization that is open to any company worldwide being involved in the business around e-mobility. During the last 3 years, a special Task Force has been extending the scope to commercial vehicles and thus, setting requirements and standards for the development of the MCS to charge heavy-duty vehicles like trucks, e-ferries, ships, and planes. The present limit of 500A and 1000V on SAE/IEC CCS couplers has motivated members of the CharIN consortium to define a set of specifications for a new coupler that can exceed megawatt charging levels, called the Megawatt Charging System (MCS). Work has begun under the IEC to create a standard based on requirements and specifications developed by industry stakeholders in the CharIN MCS work group.

DOE and its National Laboratories are involved in identifying and addressing the pre-competitive gaps, barriers, and issues associated with conductive charging of such high-power levels. There are both device and system level integration issues. Ensuring interoperability across the board is also key. National Laboratories provide a neutral and unbiased assessment of technologies and building blocks forming the MCS. Ensuring the successful development and testing of MCS is key to the adoption of EVs for medium- and heavy-duty applications and its fast charging.

v. Electricity Advisory Committee

The Energy, Security, and Independence Act of 2007 directed the DOE to establish advisory groups on implementation of smart grid technologies and energy storage. In response, DOE established, and the OE administers, the Electricity Advisory Committee (EAC) in accordance with the provisions of the Federal Advisory Committee Act (FACA), as amended, 5 U.S.C., Appendix 2. The EAC provide advice to the DOE, in implementing the Energy Policy Act of 2005, executing certain sections of the Energy Independence and Security Act of 2007, and modernizing the nation's electricity delivery infrastructure. The EAC is composed of individuals of diverse backgrounds selected for their technical expertise and experience, established records of distinguished professional service, and their knowledge of issues that pertain to the electric sector. The EAC provides significant value and insight on emerging issues and topics. The members were briefed on the vehicle grid integration report, and their expertise and knowledge were solicited and incorporated into the findings for the report.

C. Intergovernmental Coordination

It is vital that activities across agencies are coordinated, and goals aligned to minimize duplication of efforts and address challenges and barriers holistically with each agency working to tackle their piece of the overall puzzle and driving the Nation forward in a coordinated, cohesive manner. This report draws on various intergovernmental coordination efforts, including a cybersecurity agreement, and coordination efforts between DOE and NIST.

i. OE-NIST Coordination

The National Institute of Standards and Technology (NIST), a part of the U.S. Department of Commerce, has a broad mission to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life. NIST and DOE collaborate on multiple topics that relate to EVs, the electric grid, and the secure interactions of both. There is frequent and ongoing coordination and dialog between the OE’s AGR&D division and the NIST Smart Grid team to ensure awareness and integration of the two agencies’ various activities related to grid modernization. NIST’s standards and other activities are fundamental for implementation and deployment of new technologies developed by OE, as well as for the cybersecurity implications that increasing connectivity in low- and high-power environments bring. NIST has been consulted during the creation of this report but should also be considered a continuous partner in ongoing research, development, and deployment activities.

ii. Interagency Agreement with NIST to Develop a Cybersecurity Framework Profile for XFC Infrastructure

In addition to the coordination taking place between OE and NIST, DOE has an interagency agreement with NIST to facilitate project collaboration between the two agencies. In the Fall of 2021, VTO used the interagency agreement to expand upon prior work conducted by VTO and EPRI.[159] NIST will expand upon the VTO/EPRI work in developing a cybersecurity platform and certification framework for XFC and align the cybersecurity controls recommendations with the NIST CSF. For NIST's part of the collaboration, it will create a CSF for an XFC infrastructure profile, including an XFC, EV, XFC-Cloud or third-party operator, and XFC and Utility-Building network. For VTO's part of the collaboration, it will provide the data and research completed by EPRI for the XFC cybersecurity platform. The focus of this new work will be on R&D of a CSF profile, standards best practices, and practical guidance for organizations and stakeholders engaged in designing, building, installing, and/or operating XFC infrastructure. This CSF profile is intended as guidance to entities engaged in the development of a national-level risk-based approach for managing cybersecurity activities for a XFC ecosystem.

D. Consultations and Outreach

In addition to larger, formal stakeholder engagements, DOE personnel also interacted with stakeholders on a more informal individualized basis. This allowed for candid discussions that might be inhibited in a broader group. It was useful for this effort to hold these conversations with stakeholders from different parts of the ecosystem to ensure that the takeaways from the broader discussions still held true for each of the different stakeholder groups.

i. Considerations for Building the Business Cases for Bi-directional Electric Vehicle Charging

OTT produced a report discussing the considerations for building the business case for bi-directional EVs and EV charging infrastructure. The report synthesized information from existing lab studies and a series of stakeholder discussions occurring over more than 24 months. This included industry roundtables, conference panels, and a webinar series facilitated by the OTT, in collaboration with VTO and ANL, aimed at discussing these technologies. This synthesis identifies key issues and considerations that factor into stakeholder perspectives and the business cases for potential stakeholder adoption of bi-directional EVs, charging infrastructure, and other related technologies. The report, published in August 2021, can be found at

[159] The objectives of the VTO/EPRI project were to evaluate and assess cybersecurity risks to develop a reference framework network architecture of connected systems, subsystems, and communications for a xFC ecosystem. The project also conducted a cybersecurity threat and vulnerability assessment to identify and classify assets for a xFC subsystem, and recommended controls, a system architecture, and a reference design for a secure network interface card for xFC.

https://www.osti.gov/biblio/1817861-considerations-building-business-cases-bi-directional-electric-vehicle-charging.

ii. Clean Cities Listening Sessions

Clean Cities Coalitions engage in activities that support the goals and objectives of VTO's Technology Integration Program. Clean Cities Coalitions provide technical assistance and outreach to stakeholders, share peer-to-peer information at program meetings, and track and report critical program and performance metrics.

The Coalitions held stakeholder listening sessions to organize and facilitate fuel- and/or technology-specific listening sessions with experienced fleets and other relevant stakeholders to identify technology gaps and critical research needs for improving vehicle/infrastructure performance and usability.

During the 12-month project, coalitions held 17 listening sessions that focused on EVs and/or EVSE. These listening sessions involved 74 stakeholders ranging from fleet managers and maintenance technicians to general managers and administrators from public and private fleets across California, Colorado, Louisiana, Maine, Massachusetts, New York, Rhode Island, and Texas. Each listening session lasted between 1 and 2 hours and most were held virtually (employing platforms like Zoom or Skype) due to COVID-19 safety protocols.

iii. Roundtable Discussions

To gather more specific information, DOE held roundtable discussions with stakeholders. Some of the discussions were less formal and others more formal. For example, an informal roundtable took place about V2G opportunities and barriers. Here, DOE reached out to several utilities who have experience with V2G from pilot programs to hear their insights and learn more about what is needed to make the technology economically and technically viable from the perspective of utilities. The roundtables followed Chatham House rules[160]e to encourage open discussion. Participants included representatives from government organizations, vehicle and battery manufacturers, associations, utilities, and research organizations. A formal report of one roundtable was published and can be found at Bi-Directional EVs and Charging Infrastructure Roundtable Report | Department of Energy[161].

[160] "When a meeting, or part thereof, is held under the Chatham House Rule, participants are free to use the information received, but neither the identity nor the affiliation of the speaker(s), nor that of any other participant, may be revealed."[online] https://www.chathamhouse.org/about-us/chatham-house-rule. Accessed November 5, 2021.

[161] [online] https://www.energy.gov/technologytransitions/downloads/bi-directional-evs-and-charging-infrastructure-roundtable-report

V. Conclusion

The DOE VGI Initiative will advance capabilities necessary for the United States to cohesively accomplish transportation electrification, grid modernization, renewable energy resources integration, climate change mitigation, enhancing energy security and resilience, and ensure equitable access. The goal of integrating EVs onto the electric grid is to harmonize the EVs transportation mission with the U.S. electric infrastructure mission, fulfilling societal and environmental obligations.

The transportation sector and electric grid represent the backbone of the U.S. economy and way of life. While each has evolved independently, the transition to EVs will require the coupling of these two sectors. This coupling must be based on the intelligent integration of EVs with the electric grid, referred to as Vehicle Grid Integration. VGI can enable foundational changes across the transportation and electric sectors, with vehicles no longer just being a tool for the movement of people and goods. VGI allows EVs to be a highly controllable load and mobile storage device capable of performing advanced grid services that provide value to the vehicle owner, expanded operational capabilities for grid operators, and new markets for aggregation of these EV services.

The electrification of the transportation sector is accelerating, with more than 1.2 million new PEVs registered in the United States during 2023, which represents more than 8% of light-duty vehicle sales. Nearly all vehicle manufacturers are now, or soon will be, selling EVs and several have announced plans to shift all their models offered to electric within the next 10-15 years. These plans, in conjunction with state level requirements for EV sales, will result in tens of millions of EVs on U.S. roads in the next 10 years, referred to as EVs@Scale.

The primary mission of the electricity grid is to reliably provide electricity to end users. The grid has always adapted to meet increases in electricity use created by the introduction of new technologies, e.g., air conditioning, and it will do the same for the potentially large increase in loads created by the electrification of the on-road transportation sector. Transportation electrification is happening at a time of several other influences on the grid, such as distributed solar, energy storage, responsive buildings, and increased needs for resilience. The modernization of the grid, coupled with VGI, is essential to providing nationwide and equitable access to EVs. Without both modernization and VGI, the increased loads on the grid at the distribution and transmission levels could result in grid resilience and reliability problems, especially in rural and underserved communities.

VGI represents a multifaceted problem, but when done properly has potentially significant resilience, reliability, and economic benefits to the country. Appropriately planned and implemented VGI will benefit all electricity consumers, including individuals and businesses, not only grid operators and EV owners.

EVs are not like conventional loads on the grid. Since they typically are connected to the grid for long periods of time and the time when and rate at which they are charged is controllable, they can provide a wide range of grid services, such as peak shaving, load shifting, and demand response. Providing grid services by controlling charge is referred to as V1G. Since EVs also have large batteries, ranging from tens to hundreds of kWh, they also have the potential to be mobile power export devices, referred to as V2X. V2X capable EVs could provide power to homes (V2H), buildings (V2B), and the grid (V2G). This would allow V2X capable EVs to provide even greater grid services such as back-up power in emergencies and potential assistance to black start operations.

EVs providing grid services can not only help support grid resilience and reliability, but they can also help defer the need for grid infrastructure upgrades. Realizing these benefits will require proper VGI to be implemented. Stakeholders in the transportation and electricity sectors will need to collaborate, share information, and address techno-economic challenges, codes and standards issues, and cybersecurity concerns. These challenges span the entire EV charging ecosystem, including the EV, the EVSE or charger, and the distribution, transmission, and generation systems of the grid. Overcoming these challenges and aligning all the pieces of the ecosystem to be fully integrated will require a significant body of work, but the benefits to the country are undeniably worth the effort.

DOE has been conducting RDD&D activities related to integration of EVs with the grid for years, and as both sectors have evolved, these efforts have been increasingly coordinated. The Department has studied specific aspects of VGI covering impacts on EVs and the grid, grid services, codes and standards, and cybersecurity for this report. The VGI study was based on the work performed and being conducted across the DOE complex, consultations with NIST, review of reports and studies by non-DOE researchers and VGI stakeholders, and input received directly from stakeholders. Detailed takeaways from the study are presented in detail in each subsection of Section II of this report. Table V.1 below contains key takeaways that have been gleaned from Section II.

Table V.9. Key Section II Takeaways.

VGI Aspects	Key Takeaways
The use of electric vehicles to maintain the reliability of the electric grid	EVs have the capability to provide various grid services that support grid reliability, but these capabilities have only been evaluated in simulation or small-scale demonstrations in the United States. EVs providing grid services will depend on the availability of the vehicle, the existence of incentives, the implementation of enabling technologies such as controllable V1G or V2X-capable EVSE, SCM, or DERMs, and ultimately if the EV owner decides to participate in these services. Using spent EV battery packs for stationary grid storage has merit but faces significant barriers to market viability that must be resolved.
The impact of grid integration on electric vehicles	Battery degradation is impacted by both normal vehicle use and providing V2X services. Since both are scenario dependent there will not be a single result for whether V2X degradation is either negligible or significant. There is great uncertainty of the potential impacts of V2X on EV batteries. More independent testing and data are needed before vehicle manufacturers will make bi-directional operation widely available.
The impacts to the electric grid of increased penetration of electric vehicles	The addition of EVs onto the electric grid represents an increase in overall loading on the system. Increasing EV adoption could create problems or opportunities at all levels of the power system (distribution, subtransmission, and transmission), which will require more investigation at both the local and system levels. Issues will likely first appear at the distribution level where aging and capacity constrained infrastructure are likely to cause problems. Optimized electricity and transportation infrastructure requires planning, incentivized control, and incentivized behavior.
The research on the standards needed to integrate electric vehicles with the grid	The cross sectoral nature of the EV ecosystem, with unclear delineation of responsibilities, and competing priorities of standards setting organizations, makes establishing a comprehensive, commonly accepted, interoperable set of standards for EVs, EVSE, and the grid very difficult. A unified stakeholder strategy to address gaps in and harmonize standards for VGI is needed. Harmonization is essential for U.S. and international standards.

VGI Aspects	Key Takeaways
The cybersecurity challenges and needs associated with electrifying the transportation sector:	Large-scale VGI creates new cybersecurity challenges and vulnerabilities to the transportation sector and the grid that must be addressed. Cybersecurity must be continually addressed in response to ongoing and evolving threats. A holistic cybersecurity approach is required with greater stakeholder coordination and harmonization, as well as significant technology advances.

The Department has also developed specific recommendations for addressing the challenges and issues associated with VGI. These recommendations, based on the takeaways above and the results of the VGI study, are found in each of the Section II subsections and are listed in Section III of this report. Key aspects of those recommendations are summarized and highlighted in Table V.2 below.

Table V.10. Key Section III Recommendations.

#	Summary Recommendations
1	DOE could conduct RDD&D to optimize and advance the capability of EVs and EVSE to provide grid services and accelerate market adoption.
2	DOE could work with electric utilities to help coordinate the integration of EVs into an overall optimized DER framework (high renewable DER adoption) to not only promote management of the increasing population of EVs, but also generalize them as another resource to allow utilities easier integration into their operating procedures.
3	DOE could conduct further analyses, evaluations, and demonstrations to quantify the effectiveness of planning, operational, charge management, and V2X VGI strategies to identify which strategies provide the most value to the grid, especially for future EVs@Scale adoption.
4	DOE could work with stakeholders to develop tools for assessing the impacts of high-power charging of light-, medium-, and heavy-duty vehicles on utility distribution and transmission systems and develop innovative strategies and technologies to minimize the impacts, especially in dense urban, rural, and capacity constrained areas.
5	DOE could develop and demonstrate VGI/SCM approaches to reduce grid impacts of on-road light-, medium-, and heavy-duty EV charging. SCM strategies should be vocation-specific, including control strategies requiring either temporal or locational charge flexibility to meet charging needs while mitigating grid impacts and providing value.
6	Public funds expended for EVs and EVSE charging infrastructure could require smart communication capability and open access and/or local control options (i.e., non-proprietary communication) to ensure the opportunity to implement SCM programs.

#	Summary Recommendations
7	DOE could work with stakeholders to develop a unified codes and standards strategy which identifies and addresses gaps and competing standards and achieves consensus on requirements for high-level communications, connectivity, interoperability, cybersecurity, resiliency, safety, backward compatibility, future proofing, and metrics for VGI.
8	DOE, in collaboration with NIST, DHS, and other Federal agencies, could work with stakeholders to identify key VGI cybersecurity challenges and vulnerabilities to inform the development of a comprehensive VGI cybersecurity roadmap. This roadmap should include formation of a cross-sector ISAC, creation of education and workforce development programs, establishment of cybersecurity testing procedures, platforms, and protocols, and development of mitigation strategies for supply chain cybersecurity vulnerabilities.
9	DOE, in collaboration with stakeholders, could conduct RDD&D activities to address incentives that are required to enable VGI capabilities.
10	DOE, in collaboration with stakeholders, could conduct RDD&D activities on technologies that enable adoption of EVs and EVSE with V2X capabilities that enhance VGI.
11	DOE could, working with industry partners, conduct research to address EV battery pack reuse barriers associated with safety, transportation, and handling, reliability, and cooling to enable second life use of spent EV batteries.

To support the VGI Program, the Department has developed a 10-year roadmap of DOE VGI RDD&D to implement the recommendations in this report, and to address the VGI challenges and issues that fall within the purview of DOE. This roadmap details how a cross-Departmental team will cooperatively lead RDD&D efforts focused on SCM, HPC, grid operations and controls, codes and standards, and cybersecurity. This team, comprised of EERE, OE, OTT, and CESER, conducted the VGI study detailed in this report and developed the DOE VGI Roadmap to ensure that activities across all offices are properly coordinated and all VGI challenges and issues are appropriately addressed. The DOE team will work with other Federal agencies and a broad spectrum of stakeholders to implement the VGI Program.

VGI is critical to the electrification of the transportation sector and the modernization of the electric grid. While the cross-sectoral challenges to VGI are sizeable, they can be overcome and DOE is prepared to conduct the RDD&D needed to establish U.S. leadership in VGI, create good paying U.S. jobs, and contribute to combating climate change.

VI. Appendices

List of Figures

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List of Acronyms

21CTP: 21st Century Truck Partnership

21CTP-ETT: 21st Century Truck Partnership-Electrification Tech Team

AC: Alternating Current

ADMS: Advanced Distribution Management Systems

AGR&D: Advanced Grid Research & Development

Ah: Amp-hour

AMI: Advanced Meter Infrastructure

ANL: Argonne National Laboratory

ANSI: American National Standards Institute

Auto-ISAC: Auto Information Sharing and Analysis Center

BED: Burlington Electric Department

BEV120: Battery Electric Vehicle with 120-mile range

BIL: Bipartisan Infrastructure Law

BMS: Battery Management System

BTM: Behind the Meter

BTMS: Behind-the-Meter Storage

C2M2: Cybersecurity Capability Maturity Model

CAFE: Corporate Average Fuel Economy

CAISO: California Independent System Operator

CC: Constant Current

CCS: Combined Charging System

CESER: Office of Cybersecurity, Energy Security, and Emergency Response

CharIN: Charging Interface Initiative

CIP: Critical Infrastructure Protection

CNO: Charge Network Operator

CPP: Critical Peak Pricing

CPS: Cyber-Physical Security

CSF: Cybersecurity Framework

CTEP: California Type Evaluation Program

CV: Constant Voltage

DARPA: Defense Applied Research Projects Agency

DC: Direct Current

DCaaS: DC as a Service

DCFC: Direct Current Fast Charger

DER: Distributed Energy Resource

DERMS: Distributed Energy Resource Management System

DEVCOM: Army Combat Capabilities Development Command

DFT: Distribution Flexibility Tariff

DHS: Department of Homeland Security

DIN: German Institute for Standardization

DLA: Defense Logistics Agency

DOD: Department of Defense

DOD: Depth of Discharge

DOE: Department of Energy

DOT: Department of Transportation

DSO: Distribution System Operators

dWPT: Dynamic Wireless Power Transfer

EAC: Electricity Advisory Committee

EEI: Edison Electric Institute

EERE: Office of Energy Efficiency and Renewable Energy

E-ISAC: Electricity Information Sharing and Analysis Center

EMS: Energy Management System

EPRI: Electric Power Research Institute

ERS: Essential Reliability Services

ESGC: Energy Storage Grand Challenge

ESI: Energy Services Interface

ESS: Energy Storage System

ETRUs: Electric Transport Refrigeration Units

EV(s): Electric Vehicle(s)

EVs@Scale: "Electric Vehicles at Scale" refers to a future state of the U.S. Transportation Sector characterized by Electric Vehicles constituting a large portion of the entire on-road vehicle populations (e.g., > 25% market penetration)

EVSE: Electric Vehicle Supply Equipment

EVSP: Electric Vehicle Service Provider

eVTOL: Electric Vertical Takeoff and Landing

FACA: Federal Advisory Committee Act

FEMP: Federal Energy Management Program

FERC: Federal Energy Regulatory Commission

FMCSA: Federal Motor Carrier Safety Administration

FY: Fiscal Year

G&I: Grid and Infrastructure

G2V: Grid to Vehicle

GHG: Greenhouse Gas

GITT: Grid Integration Tech Team

GM: General Motors

GMC: Grid Management and Control

GMLC: Grid Modernization Lab Consortium

GMP: Green Mountain Power

GREET: Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model

GSA: General Services Administration

GVSC: Ground Vehicles Systems Center

GW: Gigawatts

HCE: Holy Cross Energy

HDV: Heavy-Duty Vehicle

HEV: Hybrid Electric Vehicle

HOV: High Occupancy Vehicle

HPC: High Power Charging

HPPC: Hybrid Pulse Power Characterization

HVAC: Heating, Ventilation and Air Conditioning

Hz: Hertz

ICEV: Internal Combustion Engine Vehicle

IEC: International Electrochemical Commission

IEEE: Institute of Electrical and Electronics Engineers

INL: Idaho National Laboratory

IOS: Interconnected Operations Services

IOU: Investor-Owned Utility

IRA: Inflation Reduction Act

IRP: Integrated Resource Planning

ISAC: Information Sharing and Analysis Center

ISATT: Integrated Systems Analysis Tech Team

ISO: Independent System Operator

ISO: International Organization for Standardization

IT: information technology

ITCA: Interoperability Testing and Certification Authorities

ITS JPO: Intelligent Transportation Systems Joint Program Office

kV: kilovolts

kW: kilowatts

kWh: kilowatt-hour

L1 120 VAC: Level 1 120 Volts Alternating Current

L1: AC Level 1

L2 240 VAC: Level 2 240 Volts Alternating Current

L2: AC Level 2

LDV: Light-Duty Vehicle

LFP: Lithium Iron Phosphate

Li: Lithium

MCS: Megawatt Charging System

MDV: Medium-Duty Vehicle

MILs: Maturity Indicator Levels

MOU: Memorandum of Understanding

MW: Megawatt

MWh: Megawatt-hours

NAERM: North American Energy Resilience Model

NAVFAC: Naval Facilities Engineering Command

NCA: Nickel Cobalt Aluminum

NCCOE: NIST National Cybersecurity Center of Excellence

NEC: National Electric Code

NEMA: National Electrical Manufacturers Association

NERC: North American Electric Reliability Corporation

NEVI: National Electric Vehicle Infrastructure

NFPA: National Fire Protection Association

NHTSA: National Highway Traffic Safety Administration

NIST: National Institute of Standards and Technology

NMC: Nickel Manganese Cobalt

NNSA: National Nuclear Security Administration

NREL: National Renewable Energy Laboratory

NRTL: Nationally Recognized Testing Laboratory

NTEP: National Type Evaluation Program

NWA: Non-Wires Alternatives

OBT: Office of Building Technologies

OCIO: Office of Chief Information Officer

OCPP: Open Charge Point Protocol

OE: Office of Electricity

OEMs: Original Equipment Manufacturers

OpenADR: Open Automated Demand Response

OpenFMB: Open Field Message Bus

OT: Operational Technology

OTA: Over-the-Air

OTT: Office of Technology Transitions

PEV: Plug-In Electric Vehicle

PHEV: Plug-In Hybrid Electric Vehicle

PII: Personal Identifiable Information

PKI: Public Key Infrastructure

PLC: Power Line Communications

PNNL: Pacific Northwest National Laboratory

PUC: Public Utility Commission

PV: Photovoltaic

R&D: Research and Development

RD&D: Research, Development, and Demonstration

RDD&D: Research, Development, Demonstration, and Deployment

RFI: Request for Information

ROI: Return on Investment

RPT: Reference Performance Test

RSAs: Registered Service Agents

RTO: Regional Transmission Organization

SAE: formerly Society of Automotive Engineers now SAE International

SCM: Smart Charge Management

SDO: Standards Development Organizations

SEPA: Smart Energy Power Alliance

SMUD: Sacramento Municipal Utility District

SNL: Sandia National Laboratory

SOC: State of Charge

SOH: State of Health

SSO: Standards Setting Organizations

TCO: Total Cost of Ownerships

TOU: Time-of-use

TWh: Terawatt-hour

U.S. DRIVE: Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability

UL: Underwriters Laboratories

V1G: as defined in Section II.C.iii of this report

V2B: Vehicle to Building

V2F: Vehicle to Facility

V2G: Vehicle to Grid

V2H: Vehicle to Home

V2L: Vehicle to Load

V2X: Vehicle to Everything

VDE: Verband Deutscher Elektrotechniker

VGI: Vehicle Grid Integration

VMT: Vehicle Miles Traveled

VTO: Vehicle Technologies Office

WECC: Western Electricity Coordinating Council

Wh/mi: Watt-hour per mile

XFC: Extreme Fast Charger

ZEV: Zero-Emission Vehicle