Impact of Electric Vehicle Charging Station Reliability, Resilience, and Location on Electric Vehicle Adoption

Bonnie Powell and Caley Johnson

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5R00-89896
August 2024

Impact of Electric Vehicle Charging Station Reliability, Resilience, and Location on Electric Vehicle Adoption

Bonnie Powell and Caley Johnson

National Renewable Energy Laboratory

Suggested Citation

Powell, Bonnie, and Caley Johnson. 2024. *Impact of Electric Vehicle Charging Station Reliability, Resilience, and Location on Electric Vehicle Adoption*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5R00-89896. https://www.nrel.gov/docs/fy24osti/89896.pdf.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5R00-89896
August 2024

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Transportation National Highway Traffic Safety Administration.

Cover Photo by Dennis Schroeder: NREL 54632.

NREL prints on paper that contains recycled content.

Acknowledgments

The authors would like to thank Everett Sargent, Jessica Suda, and Seiar Zia of the National Highway Traffic Safety Administration for providing funding, guidance, and insightful reviews. We also appreciate Kristi Moriarty (National Renewable Energy Laboratory) and Casey Quinn (Idaho National Laboratory) for sharing insights gained through their work with the National Charging Experience Consortium (ChargeX Consortium). We are also thankful to industry specialist David Vikartofsky for his participation in technical interviews cited in this report.

List of Acronyms

ADOPT	Automotive Deployment Options Projection Tool
AFDC	Alternative Fuels Data Center
ATS	Advanced Technical Services
BEV	battery-electric vehicle
BIL	Bipartisan Infrastructure Law
CCS	Combined Charging System
ChargeX Consortium	National Charging Experience Consortium
DCFC	DC fast charger
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
EV	electric vehicle
EVSE	electric vehicle supply equipment
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IK	impact protection
IP	ingress protection
NACS	North American Charging Standard
NEVI	National Electric Vehicle Infrastructure
NREL	National Renewable Energy Laboratory
PHEV	plug-in hybrid electric vehicle
PV	photovoltaics
TOU	time of use

Table of Contents

List of Figures

List of Tables

1 Introduction

A majority of electric vehicle (EV) charging events in the United States occur at home (O'Connor, Malmgren, and Perkins 2023), though public charging is critical to enable EV adoption for people without access to home charging. Therefore, large investments in time and money are being made in public charging infrastructure. These investments have been made by federal, state, and local governments, as well as utilities and private companies, since at least 2008. This investment was accelerated with the passage of the Infrastructure Investment and Jobs Act of 2021, which directed $7.5 billion toward public EV charging infrastructure. This funding is directed toward strategically located stations that create corridors to maximize EV travel range. Shortly after the passage of the Infrastructure Investment and Jobs Act (also known as the Bipartisan Infrastructure Law), a series of studies were published (see Table 2) showing both the importance of station reliability in EV purchase decisions and that many stations were not reliable.

This report explores the relationships between station reliability, station resilience, grid resilience, and EV adoption using literature reviews and analysis of EV registration and charging data. These relationships are largely outside the scope of vehicle adoption models, including the National Renewable Energy Laboratory's (NREL's) Automotive Deployment Options Projection Tool (ADOPT), so the methodology is varied. Section 2 sets the baseline for infrastructure reliability, user satisfaction, and maintenance practices. Section 3 explores the ways that electric vehicle supply equipment (EVSE) reliability impacts the relationship between EVSE and EV adoption. Section 4 shows how geographical categories such as urban, rural, large grid, off-grid, or microgrid can be helpful in EVSE deployment strategies, as well as how the relationship between EVSE and EV adoption differs among these categories. Section 5 investigates the impacts of grid reliability and infrastructure resilience on EV adoption. Finally, Section 6 reverses the perspective to examine the impact that EVs and EVSE have on grid resilience and reliability.

Note that throughout the report, in concert with the U.S. Department of Energy's (DOE's) Alternative Fuels Data Center (AFDC), a public "charging port" refers to a power supply for one EV, and a public "charging station" refers to a location that has multiple charging ports near one another.

2 Current State of U.S. Charging Infrastructure Reliability and Maintenance

EVSE needs to both be readily available and reliable in order to increase recharging convenience and decrease range anxiety. It is not enough to just have station coverage; those stations also need to be operational when needed. In recent years, there has been increased focus on EVSE reliability. In a final rule issued in February 2023, the Federal Highway Administration (FHWA) stated that it aims to address this reliability issue in three ways: (1) increasing the requirements for technical skills and qualifications of electrical technicians specifically related to electrical components of EVSE, which require proper maintenance and prompt attention; (2) requiring minimum EVSE uptime of 97%; and (3) requiring data for duration of outage and error codes associated with an unsuccessful charging session (FHWA 2023a).

To build on the foundation for charging reliability established by the FHWA's minimum standards for federally funded EV charging infrastructure projects, the National Charging Experience Consortium (ChargeX Consortium) was established to address EV charging challenges and improve public EV charging experiences (Joint Office of Energy and Transportation 2023). Three national laboratories are working with more than 50 organizations from the EV sector to address three primary EV charging challenges: payment processing and user interface, vehicle-charger communication, and diagnostic data sharing (Joint Office of Energy and Transportation 2023). Further, to ensure more reliable public EVSE, the EV Charger Reliability and Accessibility Accelerator Program will provide up to $100 million in federal funding to repair and replace existing but nonoperational EVSE (FHWA 2023b).

2.1 Types of Chargers and National Availability

There are three main categories of EV chargers: AC Level 1, AC Level 2, and DC fast chargers (DCFCs). AC Level 1 chargers use a standard 120-V AC outlet and charge at the slowest rate of approximately 5 miles of range per hour of charging (EPA 2020). AC Level 2 chargers use a 240-V AC outlet and charge slightly faster, at about 25 miles of range per hour of charging, and are typically installed in residential areas, although they also constitute a majority of public charging stations (EPA 2020). DCFCs are only available at public charging stations and charge from 200 to more than 400 miles of range per hour of charging (EPA 2020). The three types of EV charging stations and the respective connector types are included in Table 1. In the United States, SAE J1772-type chargers are currently about one-third of the market share but are being phased out and replaced with the North American Charging Standard (NACS) (currently about two-thirds of the market share). NACS began with Tesla vehicles and is being standardized as SAE J3400 (SAE International 2024).

According to a 2023 survey performed by Plug In America, approximately 90% of EV owners have at-home charging (Plug In America 2023a). This report focuses on public charging stations.

Table 1. Types of EV Charging Stations (EPA 2020)

	Level 1 Charging	Level 2 Charging	DC Fast Charging
Types of connectors	SAE J1772	SAE J1772 and SAE J3400 (NACS) [a]	Combined Charging System (CCS), CHAdeMO,[b] and SAE J3400 (NACS) [a]
Speed of charge	About 5 miles per hour of charging	About 25 miles per hour of charging	About 200–400+ miles per hour of charging
Locations found	Homes, apartments, and workplaces	Homes, apartments, workplaces, and public charging stations	Public charging stations
Availability	Widespread (standard outlets), no need to install additional equipment; automakers provide charger cords with vehicle	About 100,000 public charging ports in the United States as of 2022 (IEA 2023b)	Currently limited availability, but growing; about 28,000 charging ports as of 2022 (IEA 2023b)

[a] NACS (also known as the Tesla charging standard), currently being standardized as SAE J3400 (SAE International 2024).

[b] CHArge de Move, equivalent to “charge for moving” and a pun for “O cha demo ikaga desuka,” meaning “Let’s have a cup of tea while charging” in Japanese (CHAdeMO 2023).

Surveys and studies have found increasing issues with public charging stations in recent years. According to a 2023 survey performed by J.D. Power, although customer satisfaction with public Level 2 charging declined from 2022 to 2023 by 16 points (from 633 out of 1,000 points to 617), satisfaction with DCFCs declined 20 points (from 674 out of 1,000 points to 654) (J.D. Power 2023). In addition, Tesla’s charging network has much greater reliability than non-Tesla public charging stations, although customer satisfaction with Tesla public charging also decreased, with about 3% of EV drivers reporting nonfunctional chargers as a major issue in 2022, increasing to approximately 7% in 2023 (Plug In America 2023a). In comparison, 24% of non-Tesla drivers reported broken public DCFCs as a major issue in 2022 and 46% in 2023. It should be noted that the reliability of Tesla chargers (using the NACS connector) may change now that Tesla has opened their chargers to non-Tesla vehicles, and the experience may differ for Tesla vehicles versus other EVs.

2.2 EVSE Uptime, Reliability, and Major Causes of No-Charge Events

This section outlines the primary metric for tracking EVSE reliability (uptime), studies and surveys on EVSE reliability in the United States, and top causes of EVSE failure.

2.2.1 EVSE Uptime

The primary metric of tracking the functionality of EVSE is currently uptime. Uptime is defined as “when [a charging port’s] hardware and software are both online and available for use, or in use, and the charging port successfully dispenses electricity in accordance with requirements for minimum power level” (eCFR 2023). However, other issues such as a down payment system (i.e., credit card reader) or a non-EV parked and blocking access to a charger (Plug In America 2023a) are not tracked in this uptime calculation and could prevent a successful charging session (Ferris 2023). Uptime—as defined by the federal government in the Bipartisan Infrastructure Law (BIL)—is calculated using Equation 1 (eCFR 2023):

$$\mu = \frac{T_{annual} - (T_{outage} - T_{excluded})}{T_{annual}} * 100 \tag{1}$$

where:

$\mu =$ port uptime percentage

$T_{annual} =$ total minutes in a year (525,600)

$T_{outage} =$ total minutes of outage in previous year

$T_{excluded} =$ total minutes of outage in previous year caused by the following reasons outside the charging station operator's control, provided that the charging station operator can demonstrate that the charging port would otherwise be operational: electric utility service interruptions, failure to charge or meet the EV charging customer's expectation for power delivery due to the fault of the vehicle, scheduled maintenance, vandalism, or natural disasters. Also excluded are hours outside of the identified hours of operation of the charging station.

The BIL requires federally funded charging infrastructure projects to have greater than 97% uptime (The White House 2023b). More specifically, each charging port must have an average annual uptime of greater than 97% (FHWA 2023a). The BIL also requires charging station data—including duration of outages and associated error codes—to be shared free of charge via an API (FHWA 2023a). In addition, the National Electric Vehicle Infrastructure (NEVI) Formula Program, established by the BIL, includes \$100 million in federal funding for repairing and replacing nonfunctional EVSE (FHWA 2023b). Funding can be used to cover up to 80% of the total project cost for both public and private EV chargers (AC Level 2 or DCFCs).

Uptime is a useful and feasible way to quantify the convenience of charging, but it has multiple limitations. Certain issues facing a customer may not be accounted for in uptime, such as broken payment systems. In addition, there are multiple exclusions to the 97% uptime requirement (such as a downed charger due to vandalism or planned maintenance) that are relevant to EVSE companies but still leave a customer without a functional charger. Lastly, uptime is typically self-reported and often conflicts with public experiences (further discussed in Section 2.2.2). The ChargeX Consortium is researching alternative metrics to measure charger functionality that better reflect public perception of charging stations. One such metric is "first-time session success," which means that a charger works on the customer's first attempt and therefore reflects optimal convenience (Quinn et al. 2024).

2.2.2 Studies on EVSE Uptime and Reliability

There are various studies estimating the current national EVSE uptime. Many of these studies survey EV drivers directly. For example, J.D. Power administered a survey of more than 15,000 EV drivers and found that 20% of respondents visited a public charger but did not charge their vehicle (J.D. Power 2023). Out of these 20% of respondents, 72% indicated that the reason for not charging was station malfunction, resulting in a 14% overall station malfunction rate (Malarkey, Singh, and MacKenzie 2023). This varied by region, with the percentage of respondents who visited a charger but did not charge increasing to 29% of visits in the Denver-Aurora area (J.D. Power 2023). In addition, 25% of Californian respondents reported that they found the public charging experience to be unreliable (J.D. Power 2023). Furthermore, the

California Air Resources Board conducted a survey of 1,290 drivers—87% of whom drive a plug-in EV, and 91% of whom were from California (California Air Resources Board 2022). The survey asked EV drivers what barriers they encountered regarding public charging, and more than 24% of respondents indicated charging station operability issues. In addition, 53% of EV drivers indicated that they have had to contact customer service regarding public charging stations.

A study published by University of California, Berkeley, and the nonprofit Cool the Earth found that only 72.5% of 657 CCS connectors (representing 181 public DC fast charging stations) in the California Bay Area were able to charge for 2 minutes or more (Rempel et al. 2022). In a study by researchers at the University of California, Davis, that is pending peer review, 10,200 public charging stations were analyzed (from 132 EVs), and 7% of these sessions were found to be unsuccessful (Karanam and Tal 2023). The charging level (AC Level 2 or DC fast charging) was not known, as failed charging sessions were too short for the authors to "effectively extrapolate the charger level for most of these sessions" (Karanam and Tal 2023). These survey findings are summarized in Table 2.

According to a 2023 survey administered by Plug In America, the top issue with DCFCs was that they were nonfunctional or broken (reported by 45% of respondents), and 46% of respondents who used DCFCs said broken chargers were either a "major concern" or a "deal-breaker for using this network" (Plug In America 2023a). In addition, the percentage of those surveyed who indicated concern about broken chargers increased from approximately 24% in 2022 to more than 45% in 2023 (Plug In America 2023a). According to another 2023 survey—the 2023 NACS Consumer Fuels Survey performed with the Transportation Energy Institute—only 38% of drivers think it would be somewhat or very easy to charge their EV away from home (Eichberger et al. 2023).

In addition to published studies and surveys, the AFDC shows the status of installed public EV charging stations nationally on a daily basis as either "available" or "temporarily unavailable" (AFDC 2023a). Temporarily unavailable stations are defined as "temporarily out of service or offline due to maintenance and plans to open again in the future" (AFDC 2023a). Planned public EV chargers are also included, indicating stations that are either permitted or under construction. On Oct. 18, 2023, the AFDC dataset showed 62,713 total installed public EV station locations (with either AC Level 2 and/or DC fast charging only), 6.7% of which were labeled as "temporarily unavailable." These nearly 63,000 stations collectively had 125,533 AC Level 2 ports and 35,462 DCFC ports. AFDC status data are only available at the station level, not the port level.

Self-reported uptime percentages by EV charging providers differ from independent surveys and studies. For example, the California Air Resources Board also conducted a survey of EV service providers, asking what each company's public charging station uptime was over the course of a week. Four out of 11 total service providers responded that their equipment has an uptime between 95% and 98%, and seven providers did not respond (California Air Resources Board 2022).

Table 2. EVSE Reliability Survey Findings

Survey	Finding	Sample Size
J.D. Power 2023 U.S. Electric Vehicle Experience (EVX) Public Charging Study (J.D. Power 2023)	14% of respondents said they visited a public charger but did not charge due to charger malfunction. 25% of Californian respondents reported that they found the public charging experience to be unreliable.	15,000 EV drivers
California Air Resources Board Electric Vehicle Supply Equipment Standards Technology Review – 2022 (California Air Resources Board 2022)	24% of respondents indicated charging station operability issues. 53% of EV drivers indicated that they have had to contact customer service regarding public charging stations.	1,290 drivers (1,122 EV drivers)
Reliability of Open Public Electric Vehicle Direct Current Fast Chargers (Rempel et al. 2022)	27.5% of CCS connectors in the California Bay Area were not functional	657 CCS connectors (181 public DC fast charging stations)
Electric Vehicle Supply Equipment Pilot Final Report (Farley, Vervair, and Czerniak 2019)	87% uptime in Washington State between October 2018 and September 2019	7 public DC fast charging ports
	82% uptime (100% uptime for non-networked ports and 78% uptime for networked ports) in Washington State between October 2018 and September 2019	46 public level 2 charging ports (37 networked, 9 non-networked)
How Disruptive Are Unreliable Electric Vehicle Chargers? Empirically Evaluating the Impact of Charger Reliability on Driver Experience (Karanam and Tal 2023)	7% of public charging sessions were found to be unsuccessful	10,200 public charging stations (from 132 EVs)
Plug In America 2023 EV Driver Survey (Plug In America 2023a)	46% of respondents who used DCFCs said broken chargers were either a “major concern” or a “deal-breaker for using this network”	3,300 EV owners and 600 people interested in purchasing an EV
Transportation Energy Institute 2023 NACS Consumer Fuels Survey (Eichberger et al. 2023)	38% of drivers think it would be somewhat or very easy to charge their EV away from home	1,000 drivers

2.2.3 Top Causes of No-Charge Events

The inverse of charger uptime is charger downtime. The time a charger is “down” may be inferred by the uptime metric, but only if the charging failure is from certain causes, as discussed in Section 2.2.1. In contrast, no-charge events at public charging stations—also referred to as charging failures—are more general, referring to times when EV drivers intend to charge their vehicle while at the station, but do not do so successfully. The ChargeX Consortium Working Group 1 identified more than 50 customer “pain points” related to public charging that could result in no-charge events. These were classified into six main categories, listed below

(Malarkey, Singh, and MacKenzie 2023). It should be noted that these pain points are relevant to current EV drivers, and there may be different issues (or different perceived severity of the same issues) for EV intenders, defined as those who do not own an EV but reported they were likely to buy one as their next vehicle.

1. **Finding** a charger (issues related to identifying and locating a charger).
2. **Accessing** a charger (access issues including physical barriers, Americans with Disabilities Act accessibility issues, and inadequate space for EVs to wait for an open charger).
3. **Starting** a charge (hardware, communication, or payment failures).
4. **Completing** a charge (issues related to successfully finishing a charging session once initiated, including lack of ability to track the charging status, charging ending early, and lower power levels leading to a longer session).
5. Getting **help** (issues related to receiving assistance when needed to assess a charger, start a charge, or complete a charge).
6. Feeling **safe and comfortable** (issues at the charging station that make the user feel unsafe and/or uncomfortable, including inadequate lighting and a lack of nearby amenities).

Most customer pain points (18 out of 52) fell into the "Starting a Charge" category (Quinn et al. 2024). Therefore, this report focuses on issues related to this category, as well as the "Completing a Charge" category, which covers related issues (such as continued power production at satisfactory levels). The customer pain points in those two categories identified as "high priority" by the ChargeX Consortium Working Group 1 are listed in Table 3. It is important to note that some customer pain points can be a result of vehicle—rather than EVSE—failure.

Table 3. High-Priority Customer Pain Points Identified by the ChargeX Consortium Working Group 1 in 2023.

Customer pain points from Category 3 (Starting a Charge) and Category 4 (Completing a Charge). Source: Quinn et al. (2024).

High-Priority Customer Pain Points: Starting a Charge Category	High-Priority Customer Pain Points: Completing a Charge Category
• Broken/missing components (screens, cables, plugs, front panels) • Cables too short • Cable management (cables on the ground, driven over, cumbersome to handle etc.) • Charger powered off or no power available • App payment or authentication does not work • Failed to start charge (vehicle or EVSE) • Required multiple attempts to start successful charge • Unclear pricing—stations should clearly display pricing structure for customer to understand, and apps should match station-posted pricing policies	• Incomplete charge—charging session stops early and cannot be restarted • Lower power than expected

High-Priority Customer Pain Points: Starting a Charge Category	High-Priority Customer Pain Points: Completing a Charge Category
• Authenticating the correct station • No cell service/Wi-Fi limiting charge initiation.	

In addition to identifying top reasons for no-charge events, the ChargeX Consortium also proposes detailed solutions to increase charging reliability. Working Group 1 outlined their suggested "minimum required error codes" to help more easily diagnose the causes of charging failures (ChargeX Consortium 2023). In addition, issues with EVSE payment systems and proposed solutions are outlined in a recent ChargeX report on payment best practices (Moriarty and Smart 2024).

Entities beyond the ChargeX Consortium have also attempted to identify top issues related to public charging session failures. The top three reasons California Air Resources Board survey respondents contacted customer service were "charging station not working," "vehicle connector on charging station was broken," and "charging station shut off during charging session"—accounting for more than 70% of respondents who contacted customer service (California Air Resources Board 2022). The next most prevalent reasons all pertained to payment issues (such as no credit card reader, not being a member of the network, or not enough service to download a required mobile app), consisting of more than 25% of those who contacted customer service (California Air Resources Board 2022).

The top problems for the nonfunctioning chargers identified in the study by Rempel et al. (2022) were the payment system and charge initiation. Plug In America's national 2023 EV Driver Survey found increased responses that "chargers are nonfunctional or broken" (45% vs. 24%) and "stations lack credit card readers" (17% vs. 10%) compared to 2022. This indicates that payment systems are one of the top problems preventing successful public charging sessions. In a national Consumer Reports survey of EV owners, 11% of respondents reported being dissatisfied with the ease of payment at public charging stations (Consumer Reports 2022b). However, nearly 50% of survey respondents were Tesla users (Consumer Reports 2022b). Payment satisfaction among non-Tesla users is likely even lower. Communication issues have been reported by others as well (Schulz 2023).

The private industry has also invested in increasing the reliability of EVSE and identifying top causes of no-charge events. EV Connect, an EV charging network company, released the most prevalent causes of charging failures from network data monitoring in 2023. These were station connectivity (55%), internal station faults and errors (38%), connector or cable issues (4%), credit card readers (1%), and display screen (1%) (Qmerit Electrification Institute 2023). This shows fewer issues with payment systems compared to other studies, most likely because EV Connect users often pay through their app rather than a credit card. In October 2021, the car manufacturer Ford began the "Charge Angels" program with the goal of identifying and repairing nonoperational EV charging stations in the Ford BlueOval Charge Network, consisting of more than 70,000 stations. However, findings have not been released publicly.

A summary of survey findings on EV charging failure causes is shown in Table 4.

Table 4. Survey Findings on Causes of Charging Failures

Survey	Finding	Sample Size
California Air Resources Board Electric Vehicle Supply Equipment Standards Technology Review – 2022 (California Air Resources Board 2022)	Top reasons survey respondents contacted customer service were: • Charging station not working (42%) • Payment issues (25%): no credit card reader, not a member of the network, not enough cell service to download a required mobile app, and other billing/payment issues • Vehicle connector on charging station was broken (17%) • Charging station shut off during charging session (11%)	1,290 drivers (1,122 EV drivers)
Reliability of Open Public Electric Vehicle Direct Current Fast Chargers (Rempel et al. 2022)	Top problems for the nonfunctioning chargers: • Payment system • Charge initiation	657 CCS connectors (181 public DC fast charging stations)
Plug In America 2023 EV Driver Survey (Plug In America 2023a)	Top issue with DCFCs was that they were nonfunctional or broken (reported by 45% of respondents)	3,300 EV owners and 600 people interested in purchasing an EV
EV Connect – network data monitoring in 2023 (Qmerit Electrification Institute 2023)	Most prevalent causes of no-charge events: • Station connectivity (55%) • Internal station faults and errors (38%) • Connector or cable issues (4%) • Credit card readers (1%) and display screen (1%)	Not reported

There are also private companies that diagnose EVSE issues and maintain, repair, and replace chargers. These companies anecdotally learn common causes of malfunction through field experience. According to an interview with David Vikartofsky, president and chief operating officer at Advanced Technical Services (ATS)—an electronic repair company repairing EVSE since 2018—communication issues (on either the charger side or vehicle side) are one of the most common sources of charging failures. Approximately 30% of the service calls ATS receives involve chargers with communication failures (D. Vikartofsky, personal communication, Nov. 21, 2023). Dispenser and connector failures also have a high failure rate, making up more than 20% of the units ATS services. Other causes of charger malfunction that ATS has seen primarily fall into four main categories: powering issues (on the charger side or vehicle side), software issues (including network issues), physical issues (such as a poor connector), and vehicle issues.

Durability is another issue that leads to EVSE failure. Although there are durability requirements that many EVSE manufacturers meet to earn third-party certifications, as outlined in Section 5.2, the majority of EVSE standards focus on safety. More durability requirements may be helpful to increase the resilience of EVSE against impact (such as dropped charging cables) and dust and water intrusion. The primary focus of EVSE testing may also currently be on safety and not durability, resulting in EVSE failures from physical damage, according to an interview with an NREL senior engineer and fueling station expert (K. Moriarty, personal communication, July 21, 2023).

Acquiring the hardware components needed to repair EVSE quickly is another issue due to high demand (Crothers 2023). According to Mr. Vikartofsky, acquiring components was particularly difficult during the supply chain issues that occurred around 2020–2021. Although these issues have largely abated, Mr. Vikartofsky also stated that acquiring power electronic components can be difficult because they are specific to each original equipment manufacturer, who may or may not be willing to provide support in the case of equipment failure.

In general, gasoline filling stations are more reliable than EV charging equipment because they are a more mature and regulated market. A service station dispensing gasoline, biodiesel, or diesel must meet stringent requirements from the U.S. Environmental Protection Agency (EPA) for liquid fuels to reduce liquid spills and vapor emissions. As a result, most of the approximately 60 components making up a service stations are UL listed (McCormick and Moriarty 2023). In contrast, EV charging stations are not regulated or inspected as stringently and consistently as gasoline stations unless required by their funding source (FHWA 2023a). In addition, gas stations are required to have an attendant on-site who can assist with any infrastructure issues and discourage vandalism. Many public EV charging stations do not have an attendant, although there are efforts to collocate charging stations near existing infrastructure such as gas stations or grocery stores (and therefore have access to attendants).

2.3 Maintenance Requirements and Relevant Trends

The frequency of failed charging events mentioned in Section 2.2 can be reduced with proper maintenance and fast repairs, performed by an increasing array of innovative business models.

2.3.1 Maintenance Requirements

Maintenance requirements for EVSE include regular cleaning (to avoid debris from damaging components), inspections of components for damage, testing the power supply for functionality, performing software updates, and addressing physical damage (including repairing or replacing parts) (Bennett and Hodge 2020; Zamanov 2023). Charging cables should be stored in a way that prevents cable damage, such as through the use of a cable management system. In addition, some companies recommend that the outlet for AC Level 2 chargers be replaced every few years (Income Power 2023a). DCFCs typically require more maintenance than AC Level 2 chargers due to having additional components (such as cooling systems).

DCFC manufacturer maintenance recommendations vary in their scope and specificity, but generally advise annual visits that include inspecting and cleaning the power unit, dispenser unit, cables, connector, and display screen, as well as testing the power output. Some manufacturers—such as ABB—also recommend that the charger be inspected before use if it is damaged due to an accident or natural disaster, if the area was flooded, or if the station was struck by lightning.

An example of specific inspection maintenance requirements for DCFCs is included in Table 5. This table is based on an operation manual from BTC Power, a U.S.-based DCFC manufacturer.

Table 5. An Example of Annual Preventative Maintenance Requirements for DCFCs

Adapted from BTC Power 350-kW High-Power DC Charger Installation and User's Manual

Category	Specifics
Power box unit and dispenser unit	• Vacuum clean internal components to remove dust • Clean air intake and exhaust vents • Replace air filters every 2 years • Tighten connections to specifications • Ensure power modules are fully seated • Check if measured voltages are within 10% of the nominal value • Perform interlock testing • Inspect power terminals and wiring
Cables	• Clean and inspect cables and ensure they are secured properly • Replace the cables every 3 years
Cooling system	• Check for cooling system leaks • Clean, straighten, and secure cooling fins, if needed • Refill coolant, if needed. Replace coolant every 5 years.
Performance testing	• Measure incoming AC voltage • Ensure touch screen and button functionality • Test charging cable functionality through the use of a measurement device such as the comemso for CHAdeMO connections (CHAdeMO 2024)

A lack of timely maintenance has led to EV charging reliability issues in the past. The AFDC estimates that average maintenance costs can be up to $400 per charger per year, depending on charging level (AFDC 2023b). EVSE manufacturers typically provide warranties that can initially cover some of these costs, and extended warranties can be purchased for an annual fee (which can be more than $800 per charger per year for DCFCs) (California Energy Commission 2018). Charger networks may also provide a maintenance plan option for an annual fee (AFDC 2023b). However, some EV charging companies do not operate their chargers directly, instead selling the equipment to a "site host" or property owner (Schulz 2023). These property owners may not continue paying for maintenance after warranties expire to save costs in the short term. One EV charging company—Blink—has responded to this issue by amending their contracts with property owners to allow Blink to shut down chargers if they are not properly maintained (Schulz 2023).

In addition, the business model of many AC Level 2 charger hardware companies is likely contributing to the decreased reliability of chargers. This business model relies on profits from the capital cost of charging equipment and regular networking fees, rather than how much a charger is utilized or a charger's uptime (Keith and Womack 2023). In addition, EVSE hardware manufacturers and EV network companies each try to push responsibility for repairs to the other. This environment has exposed a need for innovative business models to maintain EVSE.

2.3.2 EVSE Maintenance Company Business Models

The EV industry has begun to address the problem of EVSE reliability. EV network companies such as EVgo and Blink are replacing and upgrading equipment (Schulz 2023). Many companies have subscription models that offer guaranteed uptime in exchange for a monthly fee, known as "Reliability as a Service." For example, charger maintenance startup ChargerHelp! provides technicians for a fixed monthly fee (approximately $100 per station per month), guaranteeing 97% uptime (ChargerHelp! 2023). ChargerHelp! also aims to increase the number of trained EVSE technicians nationally through workforce development activities (ChargerHelp! 2023). Another company—BP Pulse, a subsidiary of BP—guarantees 99.9% uptime with their "elevate" maintenance program service.

Another business model is "Charging as a Service," an all-inclusive option that includes equipment procurement, installation, and software, in addition to maintenance. Multiple companies such as EV Connect offer this option, in addition to utilities such as Xcel Energy.

Other charger repair companies have varying financial structures and business models beyond the Reliability-as-a-Service and Charging-as-a-Service models. For example, Uptime Charger provides maintenance programs and site evaluation and commissioning services. Income Power has multiple charger service packages, as well as installation services for EVSE nationally (Income Power 2023b). Trout Electric—an electrical service—installs, maintains, and services chargers in Southern California and services other electrical equipment (Trout Electric 2023).

Two other barriers that businesses aim to address are quick access to hardware components needed for repairs and closely located technicians. Repairing hardware components can be a slow process when working through an original equipment manufacturer, on the order of 2–3 weeks for AC Level 2 chargers and 1–3 months for DCFCs, according to Mr. Vikartofsky. To reduce response times, many EVSE repair companies—including Uptime Charger and ATS—have built up an exchange stock of replacement parts in warehouses (Uptime Charger 2023). In addition, there is currently a shortage of certified electricians and technicians, particularly those with EV charging infrastructure experience. Repairing and installing chargers requires unique skills, and ChargerHelp! is currently partnering with SAE International to develop EV charger certifications for technicians (Lutz 2023).

2.3.3 Relevant EVSE Maintenance and Reliability Trends

Recent trends are impacting EVSE maintenance and reliability, including increasing modularization, decreasing variety of components, increasing self-diagnostics, and policy changes, explained further below:

1. **Increasing modularization.** There has been a trend in recent years toward more modular chargers due to their ability to provide the option to upgrade power (D. Vikartofsky, personal communication, Nov. 21, 2023). This may make it easier to repair chargers, as the charger has more swappable components. However, modules are currently unique to the original equipment manufacturer and cannot yet be swapped between brands.
2. **Decreasing variety of EVSE and components.** The EV charging industry is going through a major consolidation of charging companies and hardware companies, with at least 85 companies being acquired since 2017 (Lienert and Gregorio 2023). This

consolidation leads to greater uniformity of equipment that makes it easier to keep spare parts in supply and keep technicians trained on the specific equipment.

3. **Increasing self-diagnostics.** Mr. Vikartofsky stated that ATS uses internal diagnostic software in its business and finds the software helpful. He anticipates that the software will only get better as manufacturers improve both their EVSE and the accompanying diagnostic software. However, he noted that there needs to be a standard for diagnostic software across manufacturers in order to increase its effectiveness.
4. **Policy changes.** In addition to business models in the private sector, policy changes can impact EV reliability. For example, as of July 2023, all public EV chargers in California must undergo post-installation commissioning, as well as receive an annual certification from the California Division of Measurement Standards (Qmerit Electrification Institute 2023). The goal is to increase EV charging reliability in the state. In addition, the BIL 97% uptime requirement will likely require EVSE owners and operators to decrease maintenance response times.

3 Impact of EVSE Availability and Reliability on the Relationship Between EVSE and EV Adoption

Public EVSE reliability has much room for improvement but is expected to increase due to the trends and maintenance practices outlined in the previous section. In addition, EVSE availability is increasing as public charging stations are planned using funds from the NEVI program. This section explores the impact that EVSE availability and reliability, and changes thereof, might have on EV adoption.

3.1 Studies and Surveys Documenting the Relationship Between EVSE Availability/Reliability and EV Adoption

Both the availability and reliability of EVSE impact EV adoption. Availability refers to the prevalence of charging stations, whereas reliability refers to a charging station working when a customer needs it. Both characteristics impact the convenience of public charging. Most research focuses on the impact of EVSE availability of EV adoption rather than EVSE reliability, but the two are closely related. The impacts of each are discussed separately in Sections 3.1.1 and 3.1.2.

3.1.1 EVSE Availability

Charging availability is consistently found to be one of the biggest barriers to EV adoption in surveys of U.S. drivers; 53% of participants surveyed by Pew Research Center are “not too or not all confident” that the United States will build the necessary charging infrastructure to support large-scale adoption of EVs, and survey participants suggest this lack of station availability (or perceived availability) has impacts on EV adoption (Spencer, Ross, and Tyson 2023).

Multiple surveys asking respondents to rank their reasons for not acquiring an EV found a lack of public charging stations as one of the top responses. For example, a survey performed by the University of Chicago and the Associated Press-NORC Center for Public Affairs Research found that 80% report a “lack of charging infrastructure as a primary reason for not buying an EV” (Newburger 2023). This was consistent across rural, suburban, and metro residents. Cox Automotive found that 32% of those considering purchasing an EV in 2022 cited a “lack of charging stations in my area” as a top barrier, preceded only by the expense of an EV (at 43%) (Cox Automotive 2023). An NREL analysis of surveys conducted between 2017 and 2019 found similar results; the availability of public charging stations was identified as the third-highest reason people were not considering buying an EV (33% of respondents) (Singer 2020). A 2023 survey performed by AAA also found cost as the top barrier to purchasing an EV, followed by a “lack of charging stations” (at 59% and 56% of respondents, respectively) (Moye 2023). Deloitte’s Global Automotive Consumer Study found that a lack of public EV charging infrastructure was the fourth-highest concern (out of a list of 15) in the United States; the top concern was cost, followed by driving range and time to charge (Deloitte 2023). Plug In America’s 2023 EV Driver Survey found that “free charging at select public locations” was ranked as very influential or critical for EV intenders (and less so for current EV owners) (Plug In America 2023a).

A 2022 Consumer Reports survey of more than 8,000 U.S. participants found consistent issues with public perception of EV charging availability. The study found that charging logistics, such as “where and when I’d be able to charge it,” was the top barrier to acquiring a battery-electric vehicle (BEV) (61% of those surveyed), followed by range and costs (Bartlett 2022). For those that indicated charging logistics were preventing them from acquiring an EV, 59% selected their top charging consideration as “not enough public charging stations,” followed by lack of home charging (44%), “inconvenience of charging” (42%), “long charging times” (37%), and safety concerns while at public charging stations (8%) (Consumer Reports 2022a). The Consumer Reports survey also found that *free* public charging stations were the most likely type of charging station to encourage potential adopters to buy or lease a BEV (50% of those surveyed), followed by home charging (47%), fast charging public stations (45%), and work charging (10%) (Consumer Reports 2022a). Note that this question only asked about *free* public charging stations and did not specify the expense of other types of charging, which likely contributed to the high favorability of public charging stations. Residents of urban areas listed fast charging as more important than rural residents did, on average (Consumer Reports 2022a). Eighteen percent of respondents stated that none of those charging options would encourage them to get a BEV (Consumer Reports 2022a). These findings suggest that increased public charging availability would lead to greater EV adoption.

The degree of awareness that non-EV users have regarding public charging stations also impacts their likelihood of considering acquiring an EV. Plug In America found that intenders have more questions about public charging options (more than 25% of EV intenders versus 20% of EV owners), suggesting that public charging information gaps could be preventing EV adoption (Plug In America 2023a). Noticing charging stations in one’s area is also correlated with the likelihood of non-EV users intending to acquire an EV. An NREL study found that respondents not aware of public charging stations at their place of work, at stores (or other places they visit regularly), or in locations they pass by while driving were the least likely to report that they were considering acquiring a plug-in EV (Singer 2020). This suggests that the prevalence of charging stations indicates to drivers that there are charging options for EVs, and therefore positively influences their decision to consider purchasing one.

Table 6 summarizes the U.S. surveys that found that a perceived lack of public EV charging stations were a top barrier to EV adoption. All surveys were conducted at a national level.

Table 6. Surveys Finding That the Availability of Public EV Charging Stations Is a Key Barrier to Adoption

Survey	Finding
2023 Associated Press-NORC/University of Chicago Energy Survey (The Associated Press-NORC Center for Public Affairs Research 2023)	80% report a “lack of charging infrastructure as a primary reason for not buying an EV”
Path to EV Adoption: Consumer and Dealer Perspectives (Cox Automotive 2023)	32% of those considering purchasing an EV in 2022 cited a “lack of charging stations in my area” as a top barrier
Plug-In Electric Vehicle Showcases: Consumer Experience and Acceptance (Singer 2020)	In an analysis of surveys conducted between 2017 and 2019, availability of public charging stations was identified as the third-highest reason people were not considering buying an EV (33% of respondents).

Survey	Finding
	Respondents not aware of public charging stations at their place of work, at stores (or other places they visit regularly), or in locations they pass by while driving were the least likely to report that they were considering acquiring a plug-in hybrid electric vehicle (PHEV) or EV
AAA's 2023 EV Consumer Sentiment Survey (Moye 2023)	A lack of charging stations was identified as a top barrier to purchasing an EV (56% of respondents)
Deloitte's 2023 Global Automotive Consumer Study (Deloitte 2023)	A lack of public EV charging infrastructure was the fourth-highest concern (out of a list of 15)
Plug In America's 2023 EV Driver Survey (Plug In America 2023a)	"Free charging at select public locations" was ranked as very influential or critical for EV intenders
Pew Research Center Survey (Spencer, Ross, and Tyson 2023)	53% of those surveyed were "not too or not all confident" that the United States will build the necessary charging infrastructure to support large-scale adoption of EVs
Consumer Report's 2022 Battery Electric Vehicles and Low Carbon Fuel Nationally Representative Multi-Mode Survey (Consumer Reports 2022a)	For those that indicated charging logistics were preventing them from acquiring an EV (61% of those surveyed), 59% selected their top charging considerations were "not enough public charging stations"

In addition to surveys, numerous studies have used sales data to quantify the relationship between EVSE availability and EV adoption (Table 7). Sierzchula et al. (2014) found a statistically significant positive correlation between charging infrastructure and EV market share on a national level in many countries. On average, an increase of one charging station (per 100,000 residents) led to an increased country-level EV market share by 0.12%. In the United States, Narassimhan and Johnson (2018) determined that one additional charging station per 100,000 drivers increased BEV sales 7% and PHEV sales 3%. Causality was determined by lagging the EV sales data behind EVSE data by one quarter and observing the relationship strengthen. That same year, Egnér and Trosvik (2018) analyzed this relationship on a municipal level in Sweden and found that an increase in the number of charging ports (per 1,000 people) by 1% led to an average increase in municipal BEV share of 0.3%. This increase was higher for urban areas. However, Muratori et al. (2020) summarized 50 papers on this topic and found mixed results. For example, Miele et al. (2020) surveyed potential Canadian EV buyers and found little influence of EVSE on likeliness to purchase an EV. Cost, unfamiliarity, and risk aversion had higher influence. In contrast, Ghasri, Ardeshiri, and Rashidi (2019) surveyed households in New South Wales, Australia, and found that charging infrastructure availability was important for EV adoption.

White et al. (2022) set out to find the primary drivers behind the positive correlation between charging station density and EV adoption found in numerous studies. The commonly accepted reason for this relationship is enabling further driving range. For example, the International Energy Agency (IEA)—which publishes charging infrastructure trends—estimated that global charging infrastructure grew by 41% between 2020 and 2021 alone and claims that public fast chargers will "…encourage consumers that lack access to private charging to purchase an EV, and tackle range anxiety as a barrier for EV adoption" (IEA 2022). However, through surveys, White et al. (2022) identified perceived "higher social norms" from greater charging stations (i.e., a public belief that charging stations reflected societal support of EVs) as the primary mechanism explaining this correlation, more so than enabling further EV range.

Table 7. Studies With Quantified Relationships Between EVSE and EV Sales

Study	Finding	Location
The Influence of Financial Incentives and Other Socio-Economic Factors on Electric Vehicle Adoption (Sierzchula et al. 2014)	On average, an increase of one charging station (per 100,000 residents) led to an increased country-level EV market share by 0.12%	National level across multiple countries
The Role of Demand-Side Incentives and Charging Infrastructure on Plug-In Electric Vehicle Adoption: Analysis of US States (Narassimhan and Johnson 2018)	One additional charging station (per 100,000 drivers) led to a sales boost of 3% for PHEVs and 7% for BEVs	National level in the United States
Electric Vehicle Adoption in Sweden and the Impact of Local Policy Instruments (Egnér and Trosvik 2018)	A 1% increase in the number of charging ports (per 1,000 people) led to an average increase in municipal BEV share of 0.3%	Municipal level in Sweden

Work and home charging availability can also influence EV adoption, perhaps even more so than public charging. For example, a 2018 survey performed by the Transportation Energy Institute found that 38% of all drivers said they have the ability to charge at work, but 67% of those who currently drive an EV have the ability to charge at work (Transportation Energy Institute 2018). This could suggest that work charging availability can drive EV sales, although the phenomenon may only apply to early adopters who have already acquired an EV. In regard to home charging, 44% of those surveyed by Consumer Reports who reported that charging logistics were preventing them from acquiring an EV cited a lack of home charging (Consumer Reports 2022a). In the same survey, 47% cited home charging as the charging type that would most incentivize them to rent or buy an EV, only 3 percentage points behind free public charging stations (at 50%) (Consumer Reports 2022a).

3.1.2 EVSE Reliability

Fewer studies have directly investigated the impact of EVSE reliability (e.g., charging station uptime)—rather than availability—on EV adoption, as this is harder to determine. However, the surveys and studies documented in Section 3.1.1 finding that non-EV owners were discouraged from purchasing an EV due to the inconvenience of public charging can be logically extended to EVSE that is not operating properly. In other words, because studies have found that the availability of public charging is a barrier to EV adoption, it is logical that the reliability of EVSE also impacts EV sales.

Charger reliability dissatisfaction also extends to current EV owners, potentially influencing their decision to purchase another EV in the future. Researchers from University of California, Davis, found that 20% of PHEV users and 18% of BEV users in California did not buy another plug-in EV, based on five surveys completed between 2015 and 2019 (Hardman and Tal 2021). The researchers identified factors correlated with discontinued EV purchasing, which included charging issues such as a lack of satisfaction with public charging experiences and not having an AC Level 2 home charger (Hardman and Tal 2021). In addition, first-time EV owners may be less tolerant of public charging availability and reliability challenges than those who have owned BEVs for longer. A 2024 survey from J.D. Power found that overall BEV satisfaction between these two groups widened from 2023 to 2024, and the two areas in which the gap was largest were battery range and public charging availability (J.D. Power 2024).

Current EV drivers reverting to internal combustion engine vehicles could be a problem if EVSE reliability does not improve, as many current EV owners have indicated their dissatisfaction with charging. In a short (1-week) poll of Plug In America newsletter subscribers (which skew toward EV owners) in October 2023, 50% of respondents stated that they were either "dissatisfied" or "very dissatisfied" with public charger reliability (sample size of 562) (Plug In America 2023b). As expected, the type of charging network used impacts this response. The percentage of EV owners who were dissatisfied with public charger reliability increased to 72% for non-Tesla owners and decreased to 27% for Tesla owners, due to the availability of the more reliable Tesla charging station network (Plug In America 2023b). In 2024, Tesla began opening its charging stations to non-Tesla vehicles (Barry and Bartlett 2024). Many non-Tesla vehicle manufacturers are supplying a NACS adapter to their customers, with plans to implement the NACS connector directly on vehicles beginning as soon as 2025. As implementation of Tesla's charging network for non-Tesla BEV owners is still in its early stages, it will take time to quantify the impact of this change on overall public charging satisfaction.

3.2 Modeled Relationships and Assumptions

To further research the relationship between EVSE and EV adoption, we investigated the assumptions and relationships that existing models and organizations use.

3.2.1 Annual Energy Outlook

The U.S. Energy Information Administration (EIA) publishes an energy outlook report annually that includes EV deployment projections, most recently in 2023 (EIA 2023a). The EIA's consumer vehicle choice model includes home refueling capability but does not account for public charging infrastructure availability (or reliability) (EIA 2022).

3.2.2 ADOPT

ADOPT is a consumer choice model used to estimate light-duty vehicle sales, stock, energy consumption, and carbon emissions. ADOPT starts simulations with all the existing light-duty vehicle makes, models, and trims for a realistic representation. Future vehicle options are created endogenously by optimizing component sizing to achieve vehicle attributes that provide the greatest sales for a given set of market conditions. Sales of these vehicles are estimated based on their attributes including price, fuel cost per mile, acceleration, size, and range, and—for plug-in vehicles—aspects related to recharging including availability and per-mile recharging rates. ADOPT models how regulations and incentives influence those attributes. It characterizes consumer preferences for vehicle attributes as changing nonlinearly and by income. For example, a 1-second improvement in 0 to 60 miles per hour acceleration time in a slow-accelerating vehicle is more valuable than in a mid-accelerating vehicle, and even more important for high-income households (Brooker et al. 2015). Capturing all of these key elements enables ADOPT to match historical sales to provide confidence in its results. ADOPT has been developed and used since 2008 with support from DOE's Vehicle Technologies Office, Hydrogen Fuel Cell Technologies Office, and Bioenergy Technologies Office.

ADOPT includes two different approaches to capturing the impact of public charging infrastructure on plug-in EV sales. First, a simple inconvenience factor can be applied within the ADOPT model. ADOPT assumes that those purchasing a BEV have access (or will acquire access) to a home charger or something equivalently convenient, reliably available, and similarly inexpensive. To account for the inconvenience of long-distance travel by BEVs, including the more frequent recharging stops for lower-range BEVs and slower recharging rates when stopping, ADOPT applies an inconvenience factor that gets converted to an increased purchase price. This factor reduces as BEV range, charger speed, and charging availability approach the equivalent of a gasoline vehicle. The inconvenience factor starts at $6,000 and decreases to $0 for BEVs with ranges exceeding 250 miles and recharge speeds exceeding 50 miles per 5 minutes. The $6,000 inconvenience factor has been validated with historical BEV sales.

In 2020, researchers added a new model component to ADOPT to consider the impact of public EVSE on consumer vehicle purchasing decisions in greater detail. The methodology is outlined by Greene, Kontou, et al. (2020) and Greene, Muratori, et al. (2020). It considers the value of time to locate a charger and wait for it to charge, as well as the benefit of the ability to charge at home with an EV (which is not available for internal combustion engine vehicles). The quantification of the economic cost of public charging is applied to multiple scenarios for the state of California in Ledna et al. (2022). Scenarios included a baseline scenario (No Support), increased EVSE availability scenario (High Infrastructure), increased EV subsidies scenario (High Subsidy), and a mix of infrastructure and subsidies (Mixed). Full scenario descriptions including technology, public charging, and policy assumptions can be found in Table 1 in Ledna et al. (2022), also shown in Table 8.

Table 8. Scenario descriptions and assumptions from Ledna et al. (2022)

Source: Ledna et a. (2022)

Scenario Name	Technology Assumptions	Public Charging Assumptions	Policy Assumptions
No Support	*Low Technology:* 47% reduction in battery cost from 2019 to 2030; improvements in battery energy density, electric motor cost and power to weight ratio *High Technology:* 80% reduction in battery cost from 2019 to 2030; additional battery technology and electric motor improvements relative to *No Support*	Charger count requirements benchmarked to fleet size of 6.4M EVs in 2030 (53% BEV/47% PHEV). DCFC and L2 charger counts increase at historical (2015–2019) rates Charger count requirements benchmarked to fleet size of 7.5M EVs in 2030 (70% BEV/30% PHEV). DCFC and L2 charger counts increase at historical (2015–2019) rates	Existing federal tax credit and California CVRP rebates are assumed to continue through 2021. The Clean Fuel Reward program is implemented from 2021 to 2030 and capped at a maximum of $1500/EV. CAFE standards are held constant after 2025.
High Infrastructure	Scenarios run for both *Low* and *High Technology* assumptions	Linearly interpolate BEV and PHEV infrastructure from 2019 levels to 100% in 2030; 150 kW DCFC	Same as *No Support*

Scenario Name	Technology Assumptions	Public Charging Assumptions	Policy Assumptions
High Subsidy	Scenarios run for both *Low* and *High Technology* assumptions	Same as *No Support*	Additional state rebates following the schedule in Table C5 of Ledna et al. (2022), corresponding to investment budget required for *High Infrastructure*
Mixed	Scenarios run for both *Low* and *High Technology* assumptions	Half of *High Infrastructure* investment budget, resulting in half of chargers required to reach 100% availability added by 2030	Additional state rebates following the schedule described in Table C5 of Ledna et al. (2022), corresponding to half of the *High Subsidy* investment budget

The authors found that the High Infrastructure scenario (where EVSE availability is expanded) increased light-duty BEV sales and was a cost-effective way to do so compared to the High Subsidy and Mixed scenarios, as shown in Figure 1. Note that the study considered two technology packages—conservative battery and electric motor improvements (low technology) and more optimistic improvements (high technology)—with specific assumptions outlined in Table 8. The low technology scenario is shown in Figure 1, but the same general trends can be observed independent of technology level.

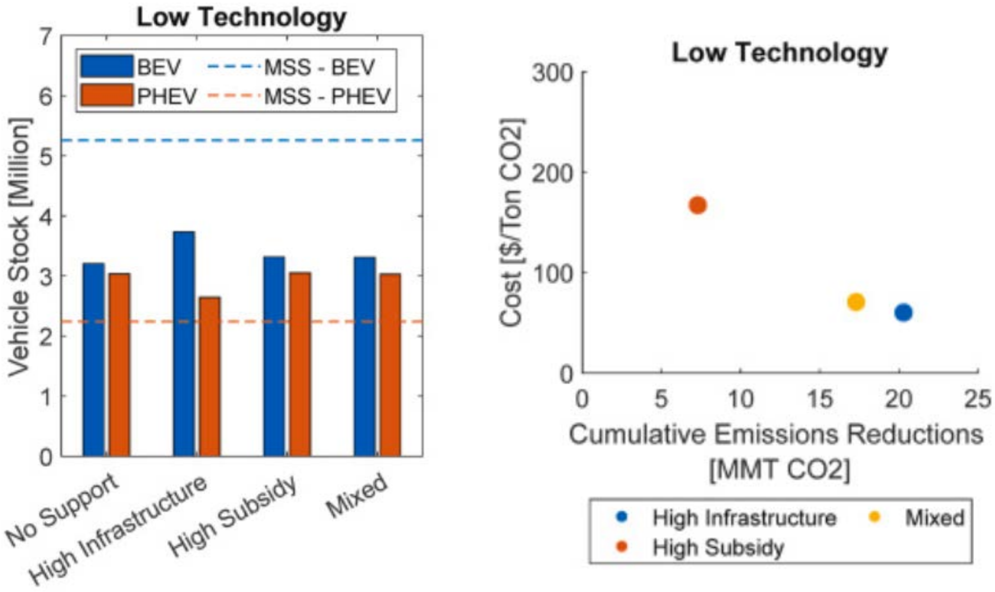


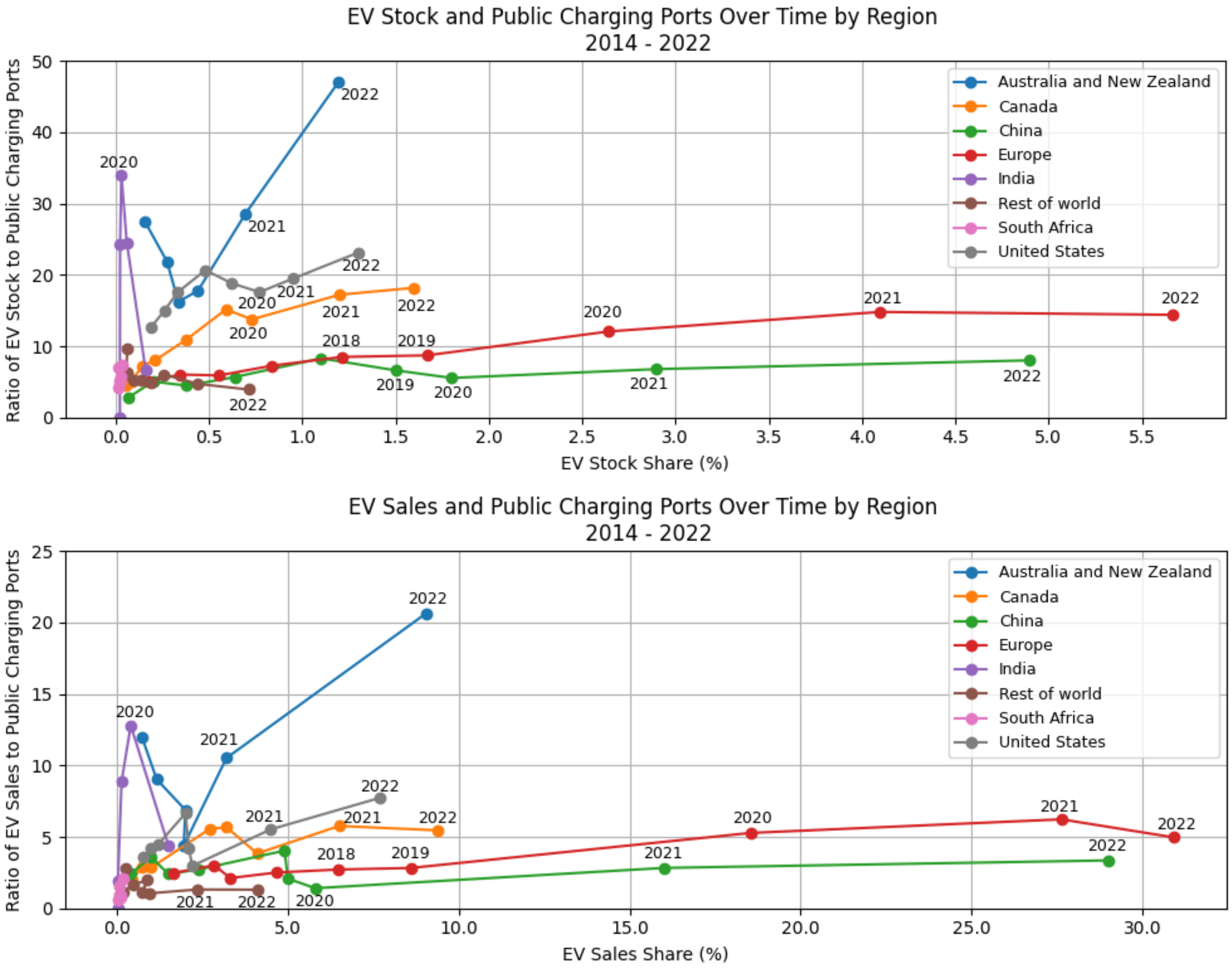
Figure 1. Results from a study modeling the cost of public charging infrastructure on consumer purchase decisions using the ADOPT model.

Left: EV stock by scenario benchmarked to the California Air Resources Board 2020 Mobile Source Strategy Scenario. Right: Cumulative carbon dioxide emissions reductions and investment effectiveness relative to the No Support scenario. Figure from Ledna et al. (2022).

It should be noted that currently, neither ADOPT method directly considers EVSE uptime.

3.3 Ratio of EV Sales and Stock to EVSE by Global Region

The relationship between EV charging infrastructure and EV ownership is quantified at a fundamental level in the ratio of EV stock to public charging ports. Therefore, it is worthwhile to investigate this ratio for different markets, as is done in Figure 2 from 2014 to 2022. The general trend is led by more developed markets—with higher EV stock shares—such as Europe and China. These regions have lower ratios, indicating there is greater charging availability. In Europe, this ratio appears to be converging at around 15 EVs per charging port, while in China the ratio is slightly less than 10 EVs per charging port. Less developed EV markets such as Canada and the United States appear to be following a similar trend, although at higher ratios. These higher ratios could partially reflect areas where there are higher shares of single-family homes that can have home chargers installed, although increasing public charging prevalence is still important for those without home charging access or for longer trips (IEA 2023c). According to SBD Automotive, the ideal ratio of EVs to public charging ports is between 8 and 12 (Miller 2023). Similar trends are also found for the ratio of EV sales to public charging ports, as shown in Figure 3. Although internal combustion engine vehicles have different refueling requirements compared to EVs, for context, there were approximately 2,000 internal combustion engine vehicles per gas *station* in the United States in 2019 (Lommele et al. forthcoming) and roughly 40 BEVs per public charging *station* in 2022 (AFDC 2024; 2023a).



EV Stock and Public Charging Ports Over Time by Region
2014 - 2022

EV Sales and Public Charging Ports Over Time by Region
2014 - 2022

Figure 2. EV stock, sales, and public charging ports over time by global region.

Ratio of EV stock (top) and sales (bottom) to public charging ports (fast and slow) and share of EV stock (top) and sales (bottom) by global region from 2014 to 2022. EV stock and sales include BEVs and PHEVs. Data from IEA and inspired by Figure 1.14 in IEA (2023b). IEA defines slow chargers as those with power ratings of 22 kW or less and fast chargers as those with power ratings between 22 and 350 kW (IEA 2023b).

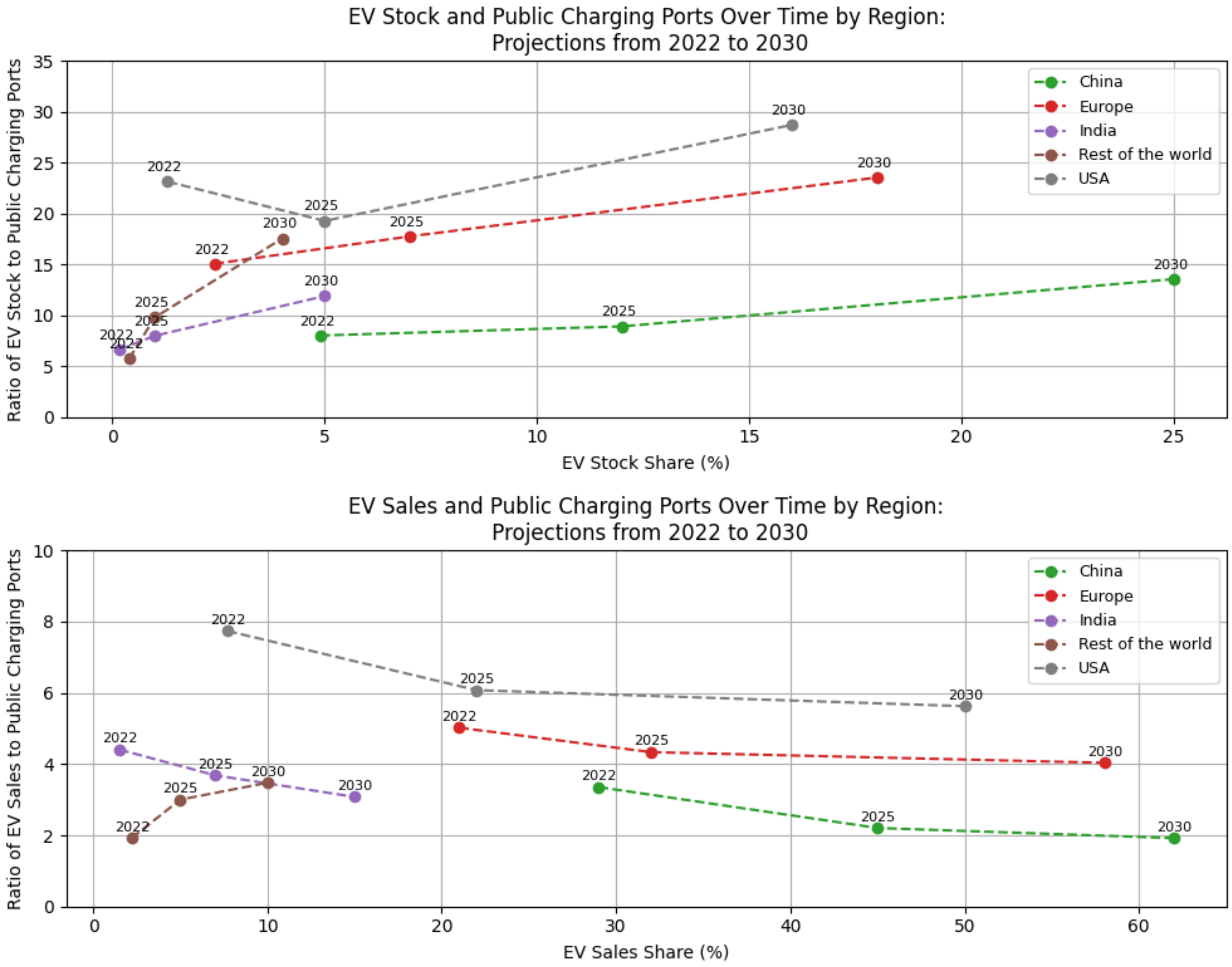
There are also major outliers that deviate from these general trends, including Australia and New Zealand, India, and South Africa.

In Australia and New Zealand, there has been a rapid growth of EV sales in recent years, and public charging infrastructure has not kept pace with this demand, leading to high EV-to-EVSE ratios. New Zealand EV sales (including BEVs and PHEVs) began increasing substantially around 2020, increasing from 2.8% of sales in 2020 to 13% in 2022 (IEA 2023b). Australia's EV sales share increased over the same time period from just over 1% to 5%. However, as of 2022, EVSE deployments according to the IEA are low in both countries (2,570 total public charging ports in Australia and 680 in New Zealand). However, Figure 2 includes data through 2022, and trends have continued to change since then. In 2023, Australian governmental support of charging infrastructure grew, resulting in an increase in both EV public charging station installations and EV sales. The EV sales share increased to more than 8% in December 2023, and DCFC installations doubled between December 2022 and December 2023 (Butler 2023). In New Zealand, the EV sales share was 27% for all of 2023 (EVDB 2023).

In India, there was limited deployment of EVSE infrastructure until around 2021, when public charging ports increased substantially from 355 public charging ports in 2020 to 10,900 in 2022 (IEA 2023b). This large EVSE investment led to a decrease in the ratio of EVs to charging ports, despite a modest increase in the EV sales share over time. There are many factors that impact this modest increase in EV adoption in India, including production requirements that limit the country's ability to import EVs and a recent increase in domestic EV manufacturing stemming from the Indian government's incentive program (IEA 2023a).

Finally, South African EV sales are shown in Figure 2 to demonstrate an outlier country that has very low EV sales (as well as few installed public charging ports), with little increase over time.

IEA projections for 2025 and 2030 are shown in Figure 3. These projections show a large increase in EV sales for the United States, Europe, and China between 2022 and 2030, and small increases for India and the rest of the world. Projections for South Africa, Australia, and New Zealand were not available. In the United States and Europe, the projections show EVSE infrastructure not keeping pace with this demand. The ratio of EV stock to EVSE for these regions increases between 2022 and 2030, and both are above the generally recommended ratio of 8 to 12. Although China's ratio of EVs to charging ports is also projected to increase between 2022 and 2030, the ratio begins at a lower—and more ideal—number. In short, public charging infrastructure will need to increase from 2022 IEA predictions to keep up with EV sales, and as suggested by the research outlined in Section 3.1, that will likely increase EV sales even further.


EV Stock and Public Charging Ports Over Time by Region: Projections from 2022 to 2030

EV Sales and Public Charging Ports Over Time by Region: Projections from 2022 to 2030

Figure 3. IEA projected EV stock, sales, and public charging ports over time by global region.

IEA projected ratios of EV stock (top) and sales (bottom) to public charging ports (fast and slow) and projected share of EV stock (top) and sales (bottom) by global region for 2025 and 2030. Projections were not available for all regions. EV stock and sales include BEVs and PHEVs. Data from IEA and inspired by Figure 1.14 in IEA (2023b). IEA defines slow chargers as those with power ratings of 22 kW or less and fast chargers as those with power ratings between 22 and 350 kW (IEA 2023b).

4 EVSE Differences by Areas

Section 3 showed that numerous factors impact the relationship between EVSE and EV adoption. Many of these factors are related to geographical area. Two geographically related categories that impact charging infrastructure and EV adoption are the urban/rural divide and areas on smaller grid networks.

4.1 EVSE Deployment Differences in Urban and Rural Areas

Most EVs to date have been adopted in urban areas, but the United States achieving its EV goals will require substantial adoption in rural areas. Charging infrastructure will need to be deployed in rural areas both for the vehicles owned by local rural residents and to enable long-distance travel between urban areas through rural areas. Rural areas face unique challenges in electricity generation and transmission and EV charging. These challenges are exemplified through the funding available to support and reduce emissions from the electric grid in rural and Tribal areas through the Inflation Reduction Act, including $9.7 billion in loans for rural electric cooperatives (The White House 2023a).

Although the definition of urban and rural differs by government agency (and even within an agency; see U.S. Department of Transportation [DOT] [2024]), for this report we loosely use one of DOT's definitions. Specifically, "urban" is defined as a U.S. Census-designated area with a population of 50,000 or greater, and "rural" refers to all remaining areas.

When deploying charging infrastructure in rural areas, some key differences must be accounted for:

1. **The density of EVs per square mile is less in rural areas.** This is because both population density and EV adoption per population are less. As mentioned in Section 3.1, Egnér and Trosvik (2018) found a positive correlation between public charging stations and EV adoption rate in Sweden. Notably, the researchers found that this correlation was higher for urban areas. In addition, the 2022 Consumer Reports survey mentioned in Section 3.1 found that residents of urban areas listed fast charging as more important than rural residents did, on average (Consumer Reports 2022a). This suggests that DCFC deployment may be less influential on EV adoption in rural areas than urban areas. In addition, baseline utilization of DCFCs is often lower in rural regions compared to denser cities.
2. **Urban (rather than local) residents may be the primary users of rural EVSE.** EV adoption is lower in rural areas of the United States, compared to urban areas (Baatar et al. 2019). In addition, there is higher residential charging access potential in rural areas compared to cities due to more people living in single-family homes with larger space. Therefore, rural DCFCs may be used more by urban residents on long-distance road trips than local rural residents. This assumption was used in estimations made by NREL's 2030 national charging network assessment (Wood et al. 2023).
3. **Traffic patterns are different in rural areas.** Light-duty vehicles in rural areas travel farther daily distances on average than their counterparts in urban areas (National Household Travel Survey 2022). This likely means that they will require extended range. A greater portion of rural traffic is on interstate highways than in urban areas (FHWA,

n.d.). Furthermore, there are fewer public places in rural areas where people want to spend time while recharging. These patterns all require a disproportionate number of DCFCs along interstates when compared to urban infrastructure.

4. **Rural areas need the most strategic deployment of EVSE in EV corridors.** Due to the patterns mentioned above, EVSE deployment in rural areas needs to be more strategic and coordinated than deployment in urban areas. The NEVI program was developed in response to this need, and it requires states to develop corridors with EVSE at least every 50 miles through rural areas.
5. **The grid has reduced capacity and flexibility in rural areas.** Charging stations have different power requirements, and power availability differs by area. Section 6.1 provides a high-level overview of electricity distribution for EV charging as context. This section focuses on the issue of single vs. three-phase power, as it is a key challenge for rural areas.

   Large power plants produce three-phase power, which is transmitted through high-voltage transmission lines over long distances. In the United States, this three-phase power is then transmitted through a mix of three-phase distribution lines and single-phase distribution lines serving a wide range of customer types. Three-phase power generally services larger loads such as commercial and industrial buildings, while single-phase distribution lines are more common for smaller residential loads. However, most distribution feeders will have a mix of three-phase and single-phase lines.

   Nearly all distribution feeders are supplied electricity from a substation, which reduces the voltage from high-voltage transmission levels down to medium-voltage distribution levels. This medium-voltage power is carried along a grouping of three-phase feeder lines across the bulk of the feeder customers, while single-phase lines will occasionally tap off this system to serve a grouping of single-phase customers or more remote areas of the feeder, as shown in Figure 4.

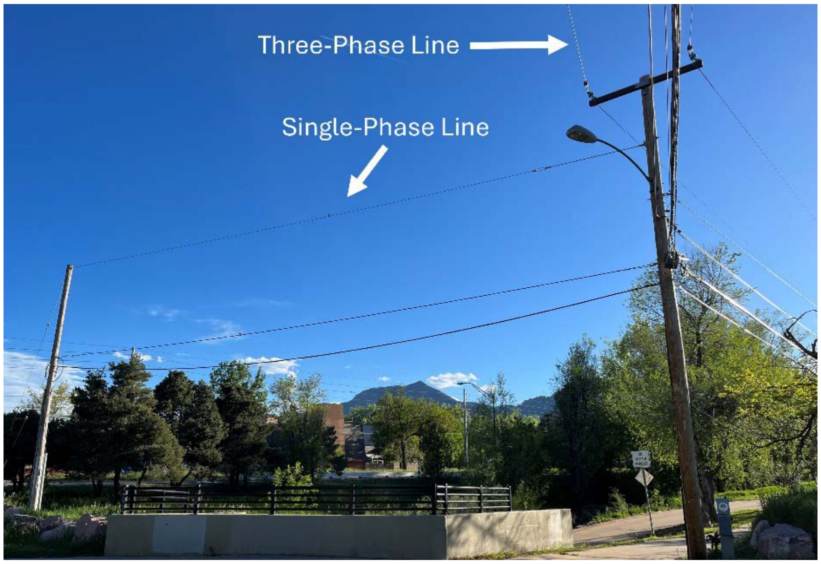


Figure 4. Annotated photo showing three-phase and single-phase distribution lines.

Photo from Bonnie Powell, NREL.

In general, the loads that are either directly fed from this main three-phase feeder line or those that are closer to the substation are more likely to have the largest excess capacity to accommodate new larger loads such as DCFCs, as shown in Figure 5.

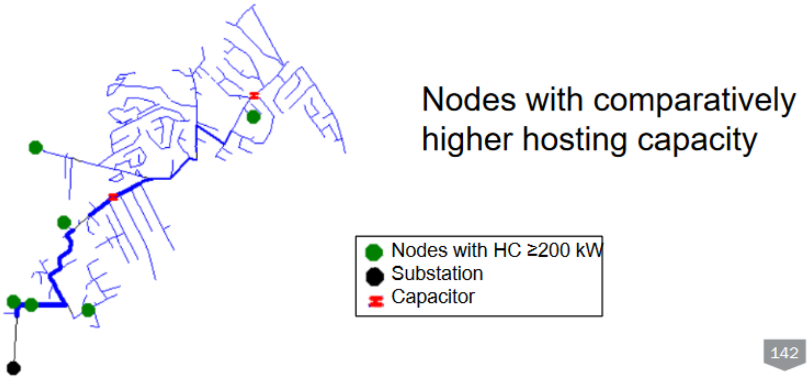


Figure 5. Distribution feeder analysis in Virginia

Figure shows that nodes closer to substations and along the main three-phase feeder line typically have higher hosting capacity. Note: HC = hosting capacity. Figure from Meintz et al. (2023).

All Level 1 chargers require single-phase 120-V AC power, while Level 2 chargers require two 120-V AC lines (to support 240-V AC charging at residential homes) or a single-phase line from a 208-V three-phase service (for 208-V charging at commercial buildings). In most circumstances, distribution feeders will generally have the capacity to support new Level 1 or Level 2 AC charging loads. However, DCFCs typically require 480-V three-phase AC power as an input and can require as much as 350 kW per charging port, a figure that is expected to grow as EV and EVSE technology matures. Although DCFCs can use single-phase power with supplementary battery and/or solar energy systems (FHWA 2023a), this generally increases upfront costs. However, a recent technology called battery-buffered DCFCs integrates a battery into each charging port (Schoeck 2023) and prevents costly grid or transformer upgrades. Battery-buffered DCFCs may be more cost-effective and have a faster construction timeline than systems requiring grid upgrades. However, these systems are currently not common, and as a result, most distribution feeders can only support DCFC loads at very select locations with the highest capacity of three-phase power.

Many rural areas primarily have single-phase power available, with insufficient capacity to support new DCFCs. Not all areas have three-phase power access, limiting the locations for DCFC installations unless three-phase distribution lines are built. There are efforts underway to expand three-phase power availability in rural areas throughout the United States.

Where three-phase power is available in rural areas, the high-voltage power (277 V and 480 V) is often available without a step-down transformer. This has implications for Level 2 charging. Level 2 EVSE with J1772 connectors cannot accept this high voltage without an expensive transformer that is often paid for by the customer (Rodney 2023). This can add great cost and delays to charging station development and can require the charging station host facility to convert over to a higher electricity tariff. This means that in many rural sites the NACS standard is preferable over J1772 for Level 2 EVSE. DCFCs are not impacted by this issue. In addition to the limitations above, rural areas are generally more susceptible to power outages than urban areas due to their remote locations. There is typically less energy infrastructure, as well as a higher proportion of overhead lines that are damaged more easily in severe weather than underground lines. In addition, rural areas are prone to longer-duration outages because areas with higher populations are prioritized for restored access when events occur. Figure 6 shows the number of counties with power outages lasting 8 hours or more for the continental United States. Do et al. (2023) found that Michigan and Louisiana had the greatest number of counties with high power outage events lasting 8 hours or more; many of these counties are rural. In addition, many rural areas have less reliable data available, as illustrated by the white spaces in Figure 6, leading to greater unknowns about the power outages in these regions.

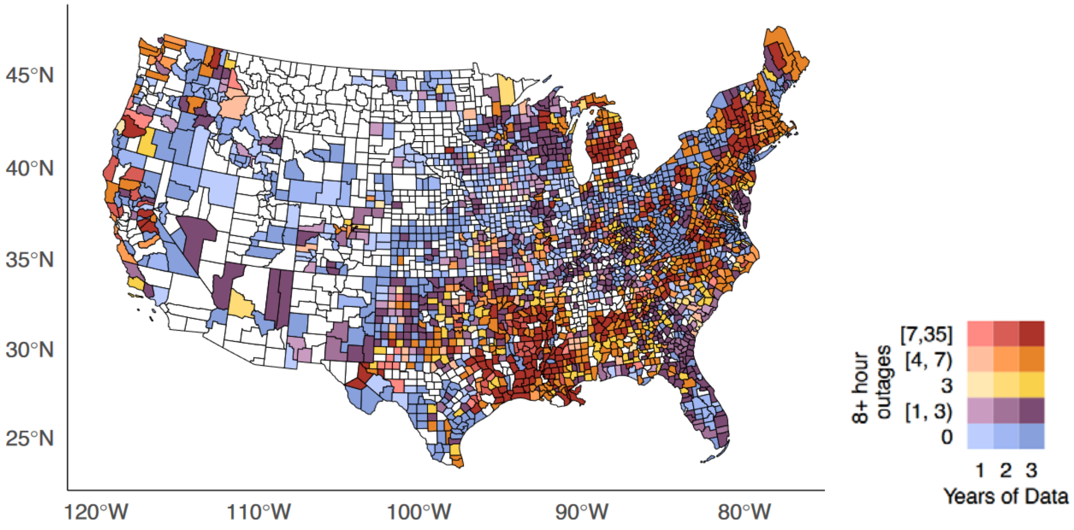


Figure 6. Average number of power outage events lasting 8 hours or more, by county, for the contiguous United States.

Areas in white did not have sufficient data. Figure from Do et al. (2023). Subset of figure is shown, full figure available in Do et al. (2023). Creative Commons license available at: https://creativecommons.org/licenses/by/4.0/.

6. **Installation costs differ between rural and urban areas.** DCFC installation costs are typically higher in rural areas compared to denser cities due to required electrical service upgrades (Smith and Castellano 2015; U.S. Department of Transportation 2024a), as outlined in point 4 above, although there are federal, state, and local grants, loans, and other financing options available specifically for rural areas (U.S. Department of Transportation 2023; 2024c).
7. **Maintenance issues differ between rural and urban areas.** Once DCFCs are installed, any required maintenance or repair will likely take longer in rural areas due to similar issues that are faced during installation including high shipping costs and longer, more expensive travel for maintenance technicians.

4.2 EV Interactions With Smaller Grid Networks

Most EVSE is connected to the larger power grid, but EVSE can also be powered by smaller grid networks including buildings with photovoltaics (PV), military bases, microgrids, and islanded

PV and battery storage. These smaller grid networks have unique opportunities and challenges and are an active area of research.

For example, a building or campus with its own energy generation source (typically rooftop PV) that is isolated from the distribution grid can be used to power nearby EVSE. The EV load can be coordinated through systems such as BP Pulse, PowerFlex, and ioTecha to minimize electric bills by utilizing electricity from PV or electricity bought from the grid during low time-of-use (TOU) rates. Electricity bills can be further minimized by charging EVs during off-peak times for the facility, therefore minimizing the facility's electric demand charges. The system can also be used to minimize emissions by taking the time-sensitive resource mix into account.

EVs can provide even greater cost and emissions savings if they (and their EVSE) are equipped for bidirectional charging. This allows the EV to provide high-value, critical backup power to the facility. This concept can also scale to multiple buildings (i.e., campus level). This is of particular interest to islanded and/or remote areas such as military bases, as it can provide load flexibility within a small grid network. A large portion of the vehicles available in 2024 are capable of bidirectional charging, and there is an increasing amount of EVSE (from at least 16 manufacturers as of 2023) capable of bidirectional charging available on the market (Smart Electric Power Alliance 2023).

However, EVs are not a direct replacement for stationary building battery storage due to their unique charging requirements and therefore require additional systems to coordinate facility load. A comprehensive managed charging strategy and system is necessary to coordinate among all equipment (including renewables) and stakeholders.

5 Impact of Extreme Weather, EVSE Durability, and Grid Resilience on EV Adoption

In addition to the causes of no-charge events listed in Section 2, EVSE uptime is also highly dependent on the electricity grid, extreme weather, the grid's resilience to extreme weather, and EVSE durability. This section explores the relationship between these factors and how they might impact charging convenience and EV adoption.

5.1 Impact of Natural Disasters and Catastrophic Events on EVSE Uptime and Repair Capabilities

EVs and EVSE face challenges and risks related to extreme weather and natural disasters. Severe weather is the top cause of major power outages in the United States, and researchers have found a strong correlation between power outage duration and precipitation and temperature change (Jackson et al. 2021). In addition to the power going out completely, charging speed reduces during cold weather (as does driving range) and may stop completely below certain temperatures. Evacuations may need to be planned more carefully to consider EVs due to shorter driving ranges and longer required dwell times for charging. If an EV is not waterproof, submersion in standing water could cause thermal runaway. Lastly, greater grid connectivity can increase the risk of cyberattacks. These are just a few examples of items that should be considered as EV adoption continues to grow.

There are multiple strategies for addressing issues posed by natural disasters or other catastrophic events. A sampling of these strategies include placing charging stations strategically around flood zones for evacuation and recovery operations; installing the control box for EV charging stations at least 18 or 24 inches off the ground for indoor and outdoor sites, respectively; providing charging station backup power through PV, batteries, or fossil fuel-powered generation; installing bidirectional EV chargers at essential facilities; developing a plan for cutting power to EVSE as needed; shading EVSE and parking spots to reduce air-conditioning load and electricity use; and increasing cybersecurity through the ISO 15118 and Open Charge Point Protocol communications protocols.

5.2 EVSE Durability Codes and Standards

There are multiple relevant codes and standards pertaining to EVSE durability. The International Electrotechnical Commission (IEC) publishes general requirements for EVSE in IEC 61851-1, including that different EVSE components meet various minimum impact protection (IK) and ingress protection (IP) ratings for both indoor and outdoor use. The specific testing standards for IK and IP ratings are described in IEC 62262 and 60529, respectively (IEC 2017). Both IK and IP ratings pertain to electrical equipment generally and are not specific to EVSE. IK ratings specify the joules of impact that equipment can withstand. IP ratings outline how protected equipment is from solid foreign objects (such as dust) and water. There are two numbers, one relating to solids and the other to water. The size of solid objects and water angle and pressure at which the equipment is protected vary based on the ratings. IEC 61851-1 also includes requirements for EVSE functionality under other environmental conditions, including extreme heat and cold, with specific testing procedures described in IEC 60068. The durability requirements included in IEC 61851-1 are summarized in Table 9.

Standards for specific connectors also have durability specifications. For example, requirements for the CHAdeMO connector are outlined in Section 23 of IEC 61851. IEC 61851-23 ("Electric vehicle conductive charging system – Part 23: DC electric vehicle supply equipment") includes specific durability requirements, referencing IEC 61851-1, IEC 62262, and IEC 60529. In addition, the SAE J1772 connector—used for AC Level 1 and some AC Level 2 charging—provides specific requirements regarding temperature and moisture (Bopp, Bennett, and Lee 2020; SAE International 2017).

Table 9. Summary of EVSE Durability Standards Included in IEC 61851-1 (General Requirements)

Impact Protection	Ingress Protection	Environmental Conditions (Cold and Heat)
Degree of protection of enclosures against mechanical impact (IK code). Testing specified in IEC 62262.	Degrees of protection against solid foreign objects and water for enclosures and interfaces (IP code). Testing specified in IEC 60529.	Operation under certain environmental conditions, including extreme heat and cold. Testing specified in IEC 60068.

Although IEC standards are international, standards for specific regions often incorporate IEC requirements. For example, in North America, UL certifies electrical equipment, including EVSE. There are different levels of UL certifications, including UL Certified, Listed, Classified, Performance Verified, and Recognized (UL Solutions 2023b). The various UL designations indicate differing levels of UL testing that the EVSE has undergone. Although many of these tests relate to safety, a UL certification can include that the EVSE meet the requirements of IEC 61851 (and therefore also meet the associated durability requirements) (UL Solutions 2023a). Although not required, most North American charging station manufacturers—including ChargePoint and Tesla—have EVSE products that are UL certified (UL Solutions 2023c).

Other relevant codes include the U.S. National Fire Protection Association's National Electric Code 625.102, which requires outdoor charging stations to be installed 24 inches above ground level for flood resistance. There are also standards for improving resilience through cybersecurity. For example, ISO 15118 includes encryption that improves resilience to cyberattack.

Cell service or Wi-Fi is also required for most EV charging stations for basic tasks such as tracking power consumption and for users to pay for charging. Ethernet connections are more reliable and could be used, but are currently very uncommon for public EVSE in the United States, demonstrated by the ChargeX Consortium findings of EVSE network connectivity issues in their *Best Practices for Payment Systems at Public Electric Vehicle Charging Stations* report (Moriarty and Smart 2024). This may be due to the significant added expense of installing ethernet conduit or the chargers being located on leased land with site hosts not having access to surrounding land where ethernet cables would need to be (Moriarty and Smart 2024; A. Powell et al. 2023). Therefore, unreliable or downed cell coverage (or Wi-Fi)—even if the grid is still operating—will likely halt public charging operations. Beyond EVs, parking lot payment kiosks can be subject to the same issues.

5.3 EVSE and EV Performance in Extreme Cold and Heat

The performance of both EVSE and EVs is negatively impacted in extreme cold and hot environments. This section explores these performance impacts for EVSE and EVs separately in Sections 5.3.1 and 5.3.2.

5.3.1 EVSE Performance

EVSE manufacturers report charging station operating temperatures within the EVSE's specification sheets. For DCFCs, these are typically in the range of −30°F to 130°F. However, performance reduces in both extreme heat and extreme cold conditions within this range. Initial results from a DOE study show that peak performance of EVSE is difficult to achieve at extreme temperatures (Meintz, Slezak, et al. 2023). A related Idaho National Laboratory report will be published in 2024.

Therefore, in regions that experience these extreme temperatures, EVSE reliability will decrease as chargers deliver less power than rated (or no power). This can lead to poor customer satisfaction and decrease EV adoption. In addition, regions with frequently high or low temperatures may not install public charging infrastructure with the same vigor as regions with more moderate climates due to concerns about extreme temperature performance. However, these concerns are typically focused more on EVs than EVSE.

5.3.2 EV Performance

Extreme cold and heat reduce EV efficiency and range through two primary mechanisms. First, the chemical reactions in the battery are inhibited at extreme cold temperatures. Second, in an attempt to minimize the efficiency penalty from these inhibitions, EVs have thermal management systems designed to keep batteries at optimal temperatures, and these require electricity from the EV to power. Third, in cold and hot temperatures, EVs consume electricity to meet the cabin occupants' heating or cooling requirements.

One of the larger studies on the impact of EV range was done on more than 10,000 vehicles of 18 popular EV models (Recurrent 2023). This study found that EV range was reduced nearly 30% in freezing conditions, with specific models ranging from 16% reduction (Audi e-tron) to 46% reduction (Volkswagen ID.4). However, range was only compared between roughly 75°F and "freezing" temperatures.

Geotab—a vehicle telematics company—more thoroughly quantified the relationship between temperature and EV range. Through analyzing 5.2 million real-world trips from 4,200 BEVs, Geotab found that BEVs were most efficient at 70°F, on average reaching a range slightly higher than the rated range (Argue 2023). This is similar to other studies; for example, Koncar and Bayram (2021) found that optimal EV efficiency was around 68°F. According to Geotab, BEVs had the lowest range in typical extreme cold temperatures (on average approximately 50% of rated in −4°F), but extreme heat actually reduced range quicker (steeper slope at temperatures greater than 70°F). Therefore, although BEV range was reduced to only around 75% of rated in 104°F, this would be even worse at higher temperatures (less typical in many places in the United States). Performance varied by BEV make and model, but the temperature-range curve shape was similar across most vehicles. Figure 7 shows these curves for the average, 90th percentile, and 10th percentile across all 5.2 million trips.

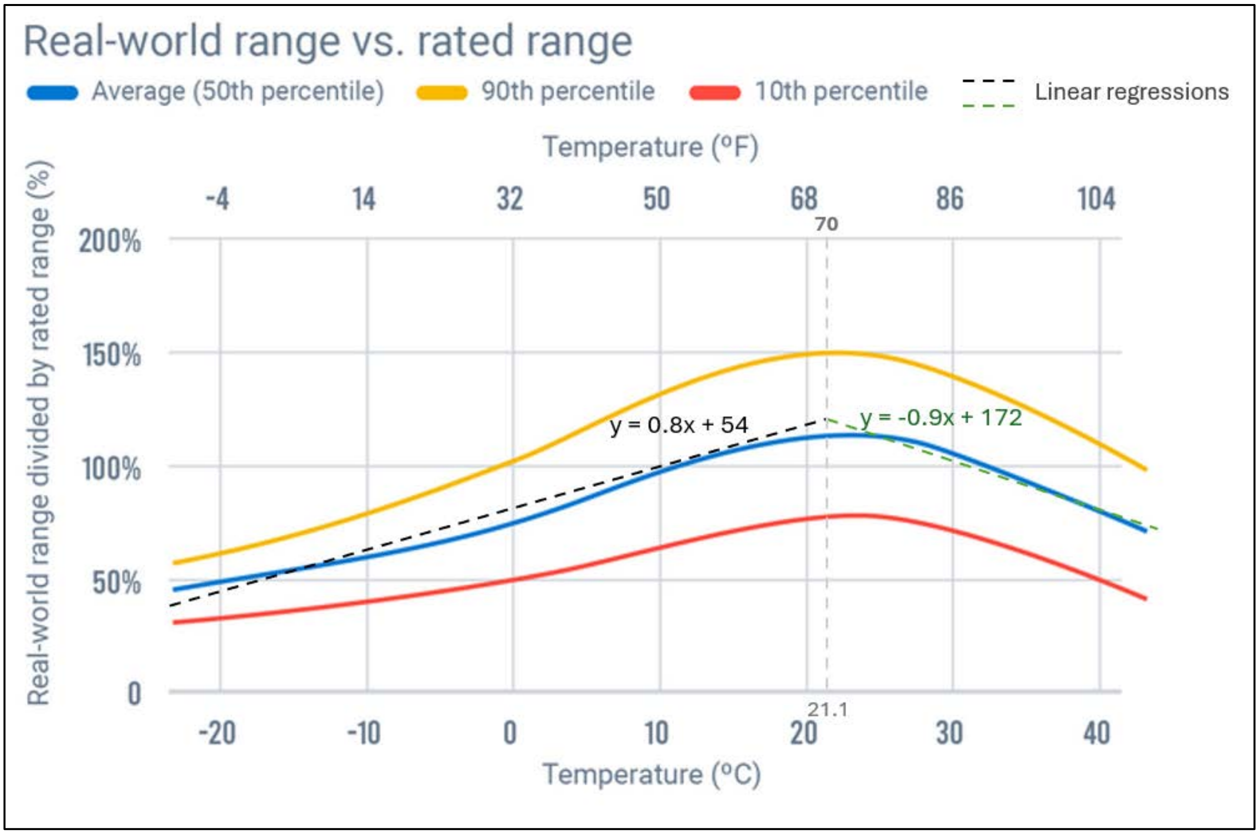


Figure 7. Temperature-range curve for 5.2 million real-world BEV trips.

Optimal range occurred at 70°F (21.1°C). Approximated linear regression equations (represented in Fahrenheit) were added for temperatures greater than 70°F (in black) and less than 70°F (in green). Source: Modified from Argue (2023).

An estimate of the impact of higher charging requirements in cold and hot temperatures on EV sales can be quantified; however, it is important to note that this assumes that a potential EV purchaser is making their vehicle purchase based on the economics of ownership.

This relationship between temperature and range allows for a strategy to quantify one component of the relationship between temperature and BEV sales. This component is the economics of fuel costs, which currently ignores other aspects such as battery degradation, reduced (real or perceived) reliability of vehicle charging, or avoidance of human exposure to extreme temperatures. These other aspects are listed in the follow-on research of the conclusions.

Focusing on the economic impacts of cold temperatures, roughly every degree decreased from the optimal temperature of 70°F decreases range by approximately 0.8% (using the linear regression line shown in black in Figure 7). Assuming range is directly proportional to both electricity consumption and costs for electricity, this 0.8% efficiency drop would be the equivalent of a 0.8% increase in payments for electricity (from increased charging needs). Decreasing the electricity rate (cents/kWh) can be a proxy for decreased electricity payments. Then, this finding can be converted to EV sales based on the approximated quantification of electricity price impact on EV sales from Bushnell, Muehlegger, and Rapson (2021) (who found a roughly 0.4% decrease in monthly BEV sales as a result of a $0.01/kWh increase in electricity rate). As a result, a cold location with an average 14°F ambient temperature should have roughly

2.4% lower vehicle sales than a warm location with 70°F ambient temperature, assuming a national average residential electricity rate of $0.15/kWh (EIA 2024). The assumptions used in this simplified example are shown in Table 10. This estimation assumes that potential EV purchasers make vehicle purchases based on lifetime economics. Research is needed to inform the other ways that temperature impacts BEV purchase decisions.

Table 10. Simplified Example Estimating the Impact of Reduced Range in Cold Climates on BEV Sales[a]

Warm location	70°F ambient temperature, 110% average real-world range divided by rated range (from Figure 7)
Cold location	14°F ambient temperature, 65% average real-world range divided by rated range (from Figure 7)
Decrease in range between locations	41% decrease in range in cold location compared to warm location
Increase in electricity rate between locations [b]	41% increase in electricity rate in cold location compared to warm location; equivalent to increasing from $0.15/kWh (2022 national average residential electricity rate, from EIA [2024]) to $0.21/kWh
Estimated monthly sales decrease	According to the linear relationship between electricity rate and monthly BEV sales found by Bushnell et al. (2021), a 41% increase in electricity rate would result in **2.4% lower vehicle sales in the colder environment**

[a] Assumes purchase decisions are economically rational and does not consider non-economic elements of purchase decisions such as battery life or human avoidance of extreme temperatures.

[b] Increase in electricity rate is used as a proxy for increased electricity costs resulting from reduced range in the cold location.

A similar estimate can also be performed for the impacts of extreme heat. Roughly every degree increased from the optimal temperature of 70°F decreases range by approximately 0.9%, using the green linear regression line shown in Figure 7. This translates to a hot location with an average ambient temperature of 104°F having an estimated 1.6% lower vehicle sales than a warm location with 70°F ambient temperature.

However, there are many factors that impact EV sales, including various incentives. It is also important to note that gasoline prices have a much higher impact of EV adoption than electricity prices, on the order of 4 to 6 times the effect, as found by Bushnell, Muehlegger, and Rapson (2021). Future work will need to better define the relationship between ambient temperature, electricity expenditures, and EV sales impacts by controlling for these and other parameters.

5.4 Relationship Between Grid Reliability and EV Adoption

Grid reliability has two potential mechanisms to impact EV adoption. An unreliable grid could discourage potential EV purchasers because they do not want to be caught without a charge on their vehicle. Conversely, an unreliable grid could increase the desirability of the battery storage that an EV offers. This storage is valuable through vehicle-to-grid and vehicle-to-building systems, as well as through high-wattage power outlets that come standard on some EVs. These outlets can power critical loads that are extremely valuable during a power outage.

To test whether either of these hypotheses was true, we looked for correlations between EV adoption and measures of grid reliability. First, we tested the relationship between EV stock share (percentage of total vehicle registrations that are battery electric or plug-in hybrid vehicles) and the System Average Interruption Duration Index (SAIDI) of the U.S. distribution grid, as reported by the EIA. This is the number of hours per year that an average customer experiences power outages over the course of a year. We also looked for a relationship between EV stock and the System Average Interruption Frequency Index (SAIFI), which reflects the relative frequency of power outages experienced by the average customer. These outages can be from severe weather, cyberattacks, equipment failures (e.g., stemming from aging infrastructure or animals), or reliability issues from a changing grid mix and retirement of nuclear and coal, among others. No statistically significant correlation was found for either metric for all years from 2017 to 2022, possibly because SAIDI and SAIFI data were available at the state level and not the county level. The state-level SAIDI and SAIFI values and EV stock shares for 2022—and the accompanying low R^2 values from a linear regression—are shown in Figure 8.

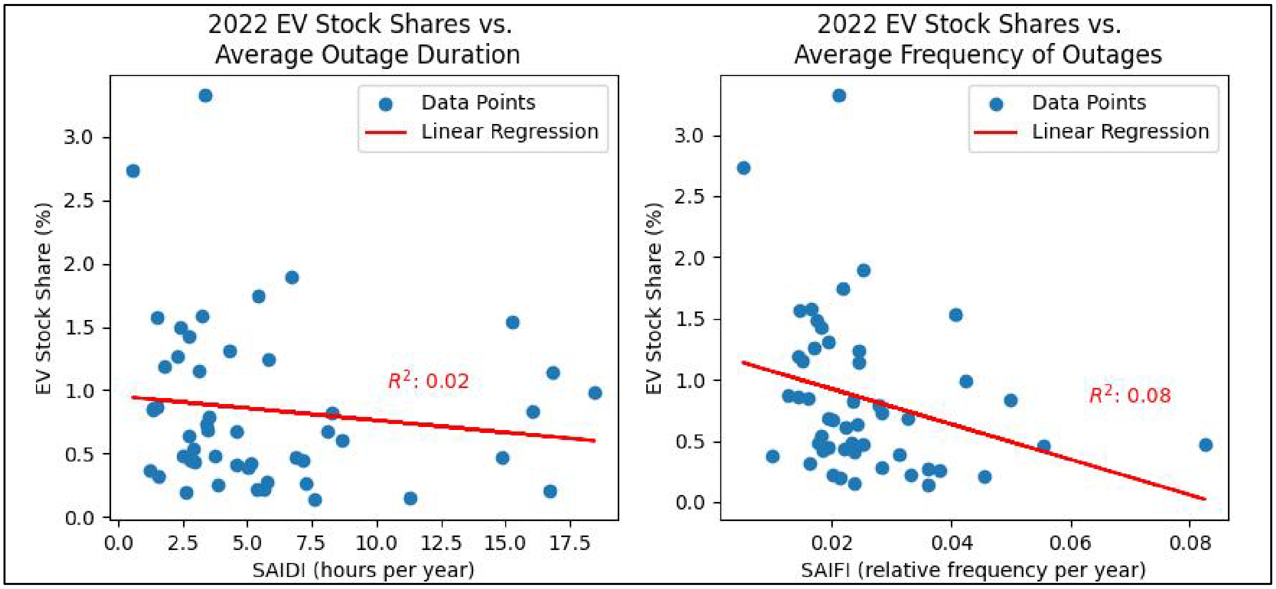


Figure 8. State-level EV stock share compared to power outage durations and frequencies.

State-level EV stock share plotted against the average number of hours per year the U.S. distribution system was down (left) and the average frequency of outages (right) for all U.S. states (except Hawaii) and the District of Columbia. SAIFI and SAIDI data from EIA (2023b).

Another way to investigate the relationship between grid reliability and EV registrations is to consider the frequency of natural hazards. Although grid outages can occur for a multitude of reasons, extreme weather is the top cause in the United States. A 2022 report by the nonprofit news organization Climate Central found that approximately 83% of major power outages between 2000 and 2021 were caused by extreme weather (Climate Central 2022).

Annualized frequency of natural hazards is reported on a county level by the Federal Emergency Management Agency (FEMA) as part of the National Risk Index (FEMA 2024b). Annualized frequency is defined as the probability of the occurrence of any natural hazard (including winter storms, hurricanes, tornados, and others) in a specific county in one year (FEMA 2024a). To determine if there is a relationship between the annualized frequency of natural hazards and EV stock, EV stock shares for 2022 and annualized frequency values were plotted, and a simple linear regression was added. Although at first glance there may appear to be a relationship, the majority of data points are located at the bottom of the figure, representing low EV stock shares, which explains the lack of relationship demonstrated by the linear regression (R^2 value of 0.05).

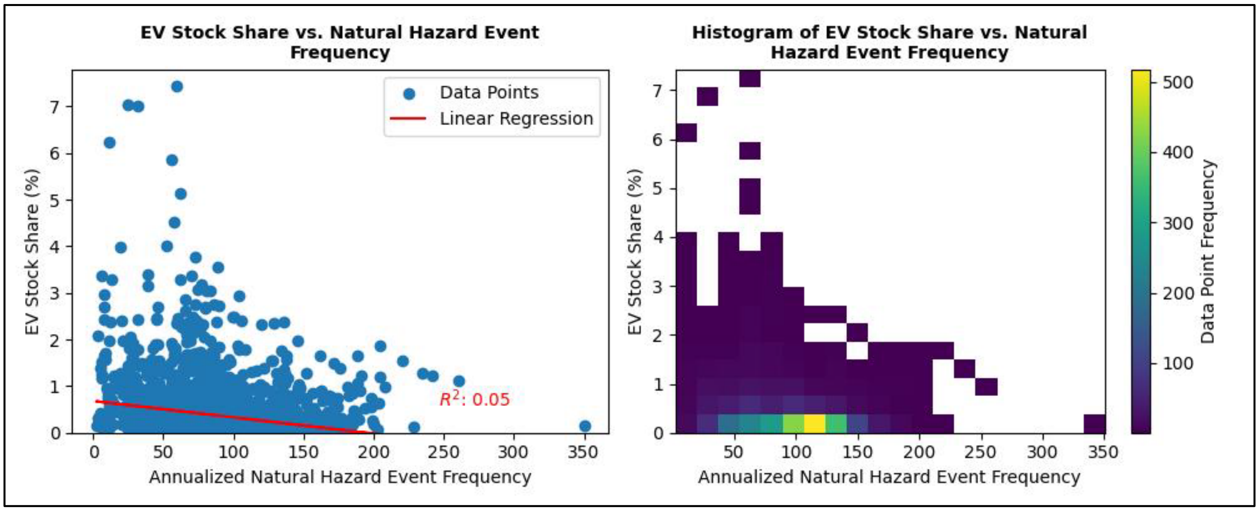


Figure 9. County-level EV stock shares for 2022 compared to annualized natural hazard event frequency.

EV stock shares vs. annualized natural hazard event frequency on a county level in the United States with a linear regression (left) and the prevalence of those data points (right). These figures show that there is no relationship between EV stock share and the frequency of natural hazards when considering all U.S. counties. EV stock include BEVs and PHEVs. Annualized frequency data from FEMA (2023). 2022 EV stock data are derived from registration counts by NREL and Experian Information Solutions.

Figure 9 shows that most counties are concentrated at the bottom of the figure, representing low EV stock shares (less than 2%). To further investigate this and determine if there was a relationship between EV stock share and annualized natural hazard event frequency only for counties that are higher adopters of EVs, two simple linear regressions were added. As shown in Figure 10, simple linear regressions for only counties with EV stock shares greater than or equal to 2% (left) and below 2% (right) were added. Both have very low R^2 values, indicating no relationship. The threshold of 2% was chosen due to the appearance from Figure 9 that counties greater than this approximate threshold may have a relationship between EV stock and natural hazard event frequencies. Thresholds of 1% and 1.5% had similar results.

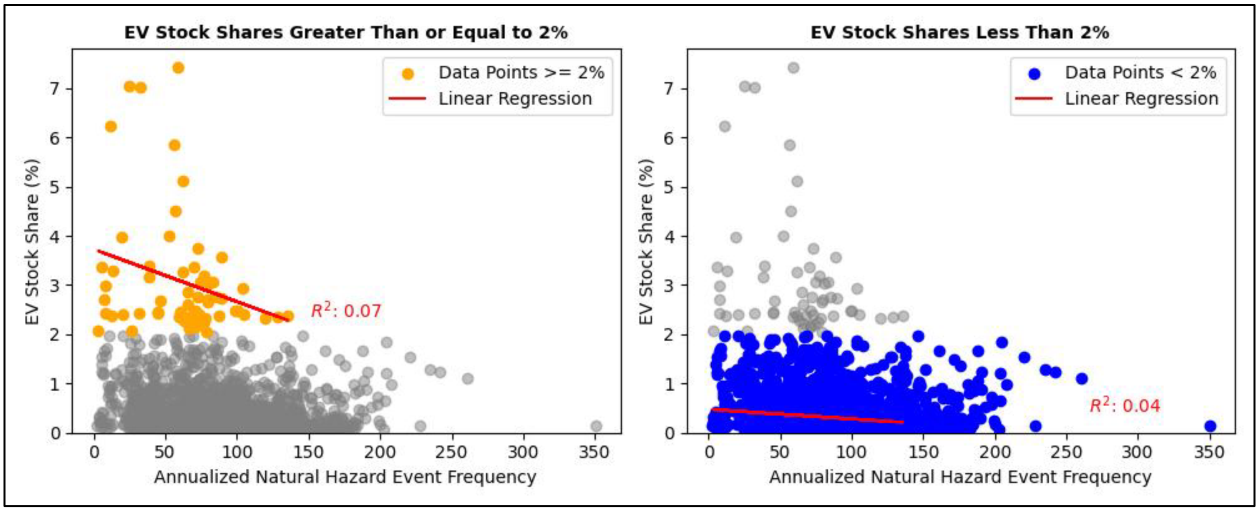


Figure 10. 2022 EV stock shares compared to annualized natural hazard event frequency for select counties.

EV stock shares vs. annualized natural hazard event frequency on a county level in the United States with a linear regression for only counties with EV stock shares that are greater than or equal to 2% of total vehicles (left) and less than 2% (right). These figures show that there is no relationship between EV stock share and the frequency of natural hazards when considering only U.S. counties with high or low EV stock shares. EV stock include BEVs and PHEVs. Annualized frequency data from FEMA (2023). 2022 EV stock data are derived from registration counts by NREL and Experian Information Solutions.

Finally, there does not appear to be a linear relationship on a state level either. The regressions between EV stock shares and annualized frequency of natural hazards for six states is shown in Figure 11.

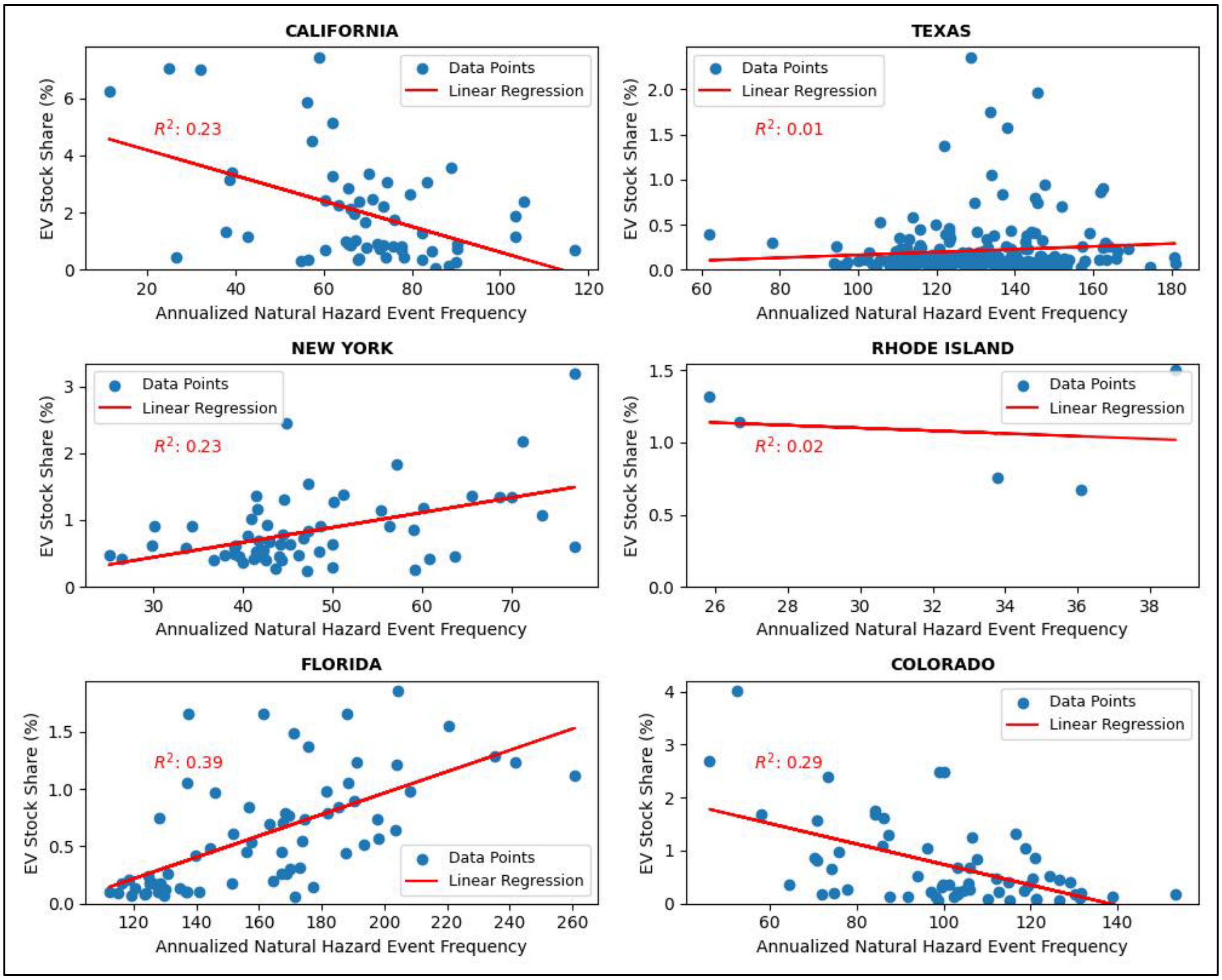


Figure 11. 2022 EV stock shares compared to annualized natural hazard event frequency for six states.

County-level annualized frequency of natural hazards vs. 2022 EV stock shares for six states, including associated linear regressions and R^2 values. National Risk Index data from FEMA (2023). EV stock include BEVs and PHEVs. 2022 EV stock data are derived from registration counts by NREL and Experian Information Solutions.

There are multiple potential reasons for this lack of relationship. One possibility is that there are two driver types canceling each other out. Residents could view a less reliable grid as a reason to avoid an EV purchase due to the potential for unreliable home charging. On the other hand, residents could view an unreliable grid as a motivator to purchase an EV for use as backup power. It is also plausible that the U.S. electricity grid is too reliable to have an impact on EV purchasing decisions, with only brief and infrequent disruptions. In other words, the reliability of the U.S. electricity grid may be high enough to have little to no impact on EV purchasing decisions. However, a more granular analysis (e.g., at the city level or income level) could reveal a relationship that the county-level analysis does not show.

6 Impact of EVs and EVSE on Grid Resilience

While it is not clear what impact grid resilience has on EV adoption, perhaps it is even more important to investigate the reverse relationship—the impact that EVs have on grid resilience. Electricity demand from EVs is projected to continue to grow in the United States and globally over time, although the 2022 World Energy Outlook projected the share of total U.S. electricity demand from EVs will be only around 6% in 2030 (IEA 2023b). This relatively low percentage is attributed to the high projected electricity demand increases for other end uses including heating, cooling, and industrial processes. Nonetheless, EV loads are not spread out uniformly and pose unique challenges to utilities, including overcoming high peak load spikes at certain times of day and in certain geographic areas.

The impact of EVs on the electric grid is therefore of utmost concern to electric utilities, who have funded numerous studies into this relationship as EV adoption grows. This section largely comprises a literature search that compiles those studies. EVs can have positive and negative impacts on grid resilience, depending on their overall load in comparison to grid capacity, how flexible their charge timing is, and how their electric load is managed and coordinated with the grid. It also depends on the grid configuration, as outlined below.

6.1 Overview of Electricity Transmission for EV Charging

The process of distributing electricity from transmission lines to EV charging stations consists of three primary categories of components: a distribution substation, distribution feeders, and on-site components. The distribution substation includes high-voltage transmission lines and transformers to reduce the voltage, while the distribution feeders distribute electricity to end users. Lastly, the voltage is lowered once again before reaching the EV charging station at a specific site. A diagram outlining the components involved in distributing electricity from the grid to EV charging stations is shown in Figure 12.

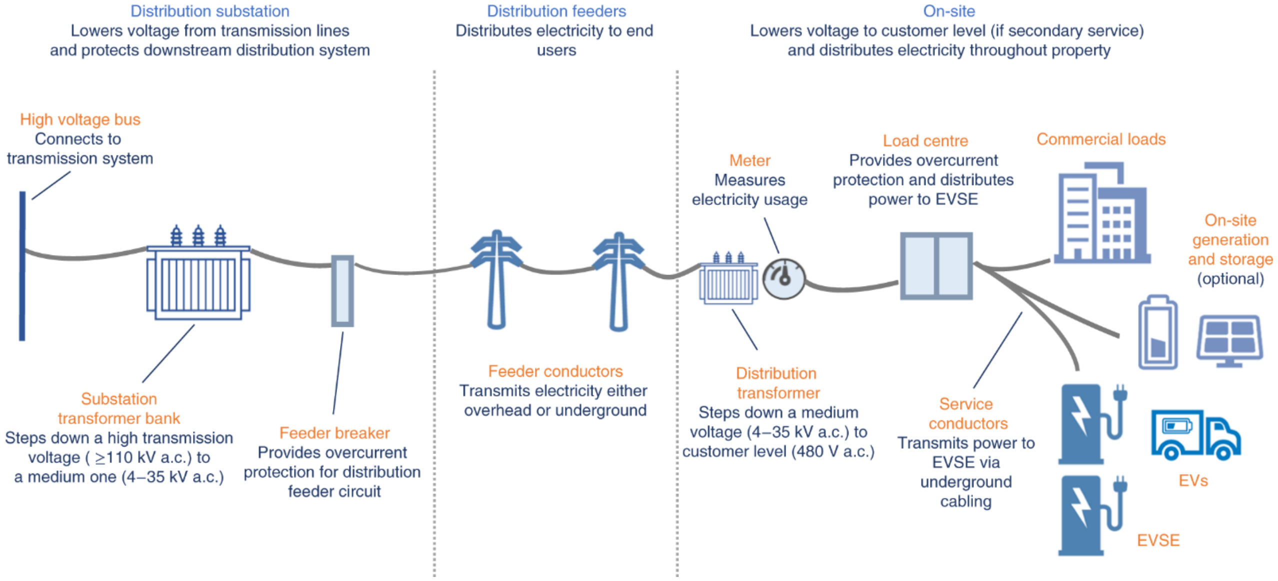


Figure 12. The key components for moving electricity from the grid to EV charging stations.

Source: Borlaug et al. (2021)

6.2 Benefits and Issues to the Grid of Nationwide EVSE Deployment

If the electric load from EVs in added to a grid in an unmanaged way (per Figure 13), the peak load requirements challenge the grid and require expensive expansions to grid infrastructure. If it can be managed, the incremental peak load is much smaller and less expensive to fulfill. Furthermore, the EV load is more flexible than other loads, so it can be moved to make the grid more adaptable to changes in electricity production or electric load. This is particularly valuable as grids source their electricity from an increasing portion of intermittent sources such as wind and solar.

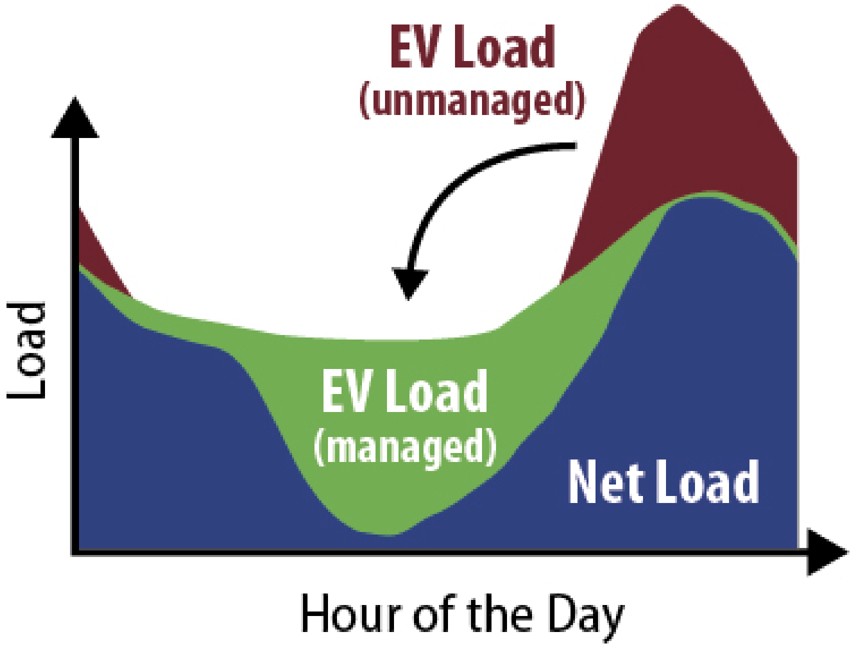


Figure 13. Diagram showing how EV charge management leads to a lower overall peak load to the utility.

A lower peak load can lead to lower infrastructure costs. Source: Anwar et al. (2022).

EVSE is heavily reliant on—and connected to—the electricity grid. Increased EV adoption along with nationwide deployment of EVSE presents both benefits and challenges to the electricity grid, either increasing or decreasing grid resilience. EVs can benefit the grid by providing load flexibility or even backup power (vehicle-to-grid or vehicle-to-building). An example of load flexibility benefitting the grid occurred in California in September 2022, when the California Independent System Operator (Cal-ISO) sent an emergency text message ("Flex Alert") to residents requesting they reduce their energy use for 3 hours to avoid power outages (Swan 2022). Cal-ISO reported this led to a reduction in electricity demand. Because EVs are one of the largest and most flexible residential loads (as shown in Figure 14), residents who choose not to charge their EV during a Flex Alert period could have a significant positive impact on the grid, potentially avoiding prolonged power outages.

The benefits of EV load flexibility can be automated and made more reliable by sending a price signal to EV owners and equipping them to respond to the price signal in an automated way, as discussed in Section 6.3.

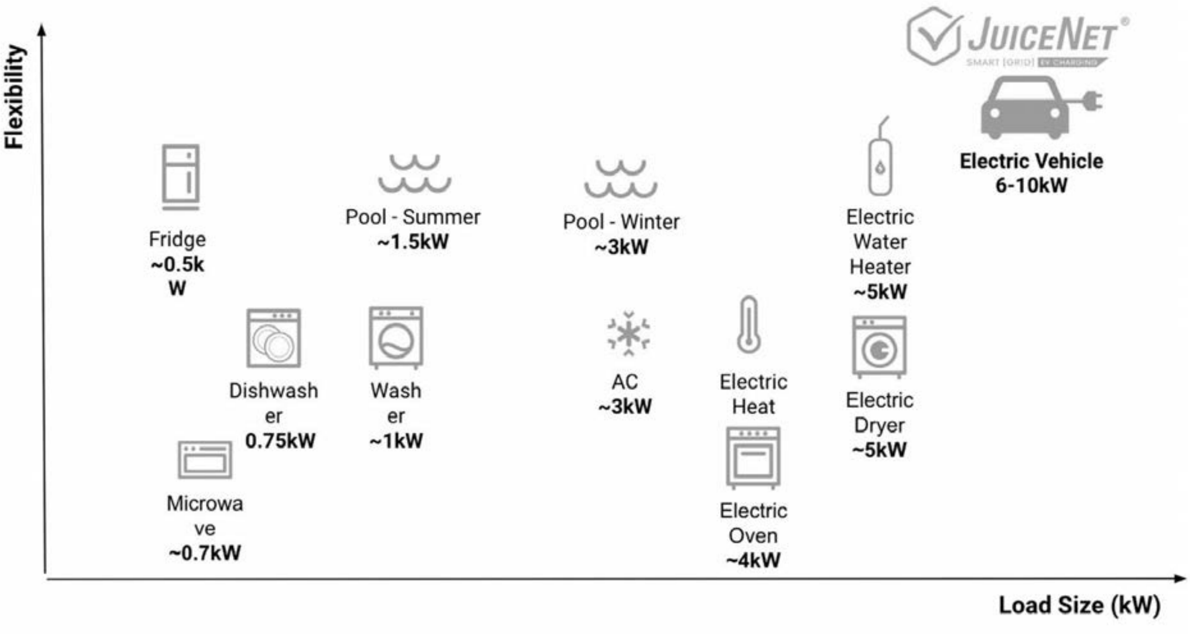


Figure 14. Various residential plug loads based on their degree of flexibility and load size.

EVs are one of the largest and most flexible residential plug loads. Source: Roper (2019).

EVs can also challenge the grid. For example, unmanaged EV charging at high EV adoption rates can lead to high peak demand spikes, especially in the early evening when commuters return home and plug in their vehicle (Muratori 2018; Jones et al. 2021). One study found that peak net electricity demand could increase by up to 25% with forecasted levels of EV adoption and by up to 50% in a full electrification scenario (S. Powell et al. 2022). This peak demand spike can lead to a host of issues including higher voltages, line loading issues in the secondary sides of feeders (rather than the primary side), and line and transformer overload (Bennett, Lave, and Scofield 2021). Higher EV adoption also comes with additional electricity demand that could make the grid more fragile in certain areas.

These challenges may require grid upgrades to accommodate EVSE, especially in high numbers and if charging is not managed. In a study performed by National Grid and Hitachi Energy modeling the impacts of fleet electrification in part of National Grid's service territory, 13 out of 19 studied distribution feeders will need capacity upgrades, assuming unmanaged EV charging (National Grid and Hitachi Energy 2021). On a larger scale, the California Public Utilities Commission estimated $50 billion of distribution grid investments are required in the state by 2035 if EV loads are not managed (Kevala 2023).

The penetration of EVs that will lead to the grid requiring upgrades (if charging is not managed) varies based on the study, with one estimate being 30%–40% of vehicles on the road (Golden 2022). The primary managed charging strategies to minimize required grid upgrades fall into two categories: (1) managing EV load over time, typically on the order of 1 day, and (2) managing EV load over geographic areas.

In addition to grid impacts, EV charging can impact building electrical systems when chargers are connected to buildings. This report focuses on grid impacts, not building electrical impacts, but readers interested in more information on EV impacts to building electrical systems can consult a study from Fernandez, Herrera, and Mérida (2020), who modeled the effects of EV charging in parking garages on building electrical systems.

6.3 Charging Management Solutions and Grid Upgrades To Accommodate EVSE

The electric load that EVs add to the grid can be managed both spatially and temporally to avoid increasing peak loads that require infrastructure upgrades (per Figure 13). Managed charging has great value to the utility because it avoids costly grid upgrades. When costly grid upgrades are avoided, utilities can pass those cost savings down to EV owners as an incentive to participate in managed charging. These incentives include TOU pricing, demand management rates, and real-time pricing, among others. The savings to EV owners may reduce the total cost of ownership in a way that is likely to increase EV sales. It has been found that electricity prices increase EV sales; for example, Bushnell, Muehlegger, and Rapson (2021) found that for every $0.01/kWh increase in the price of electricity, monthly BEV sales reduced approximately 0.4%. Therefore, it is possible that these managed charging incentives reducing the costs of charging one's vehicle would increase EV sales. This connection is explored through an example in Section 6.3.1.2.

6.3.1 Temporal EV Load Management

If EV load can be shifted from peak to off-peak times, the overall costs of EV-related grid upgrades will be minimized. This is typically done by sending a price signal to the EV owners, and can be done through traditional managed charging strategies (unidirectional from the grid to the vehicle) or bidirectional charging strategies (both from the grid to the vehicle and vice versa) (Smart Electric Power Alliance 2021).

6.3.1.1 Managed Charging Strategies

Non-Smart Managed Charging Strategies

One of the simplest ways to shift EV load away from the grid peak load is to make charging away from home comparatively less expensive. Uncontrolled, daytime charging could reduce electricity demand when compared with home charging (S. Powell et al. 2022). This involves allowing drivers to charge their EVs whenever they would like outside their home—utilizing work or public charging stations—and limiting home charging. In addition to reducing grid impacts, daytime charging can take advantage of excess electricity produced from solar PV during peak production periods (S. Powell et al. 2022). However, this solution can make EV charging more inconvenient and therefore may not be viewed favorably by EV operators.

A more commonly used strategy to move the EV peak load away from the grid net peak load is for utilities to send price signals to EV owners through TOU pricing or demand response rates (Smart Electric Power Alliance 2021). Real-time pricing is also an option but has generally only been implemented in pilot programs to date. These pricing mechanisms can encourage EV owners to charge their vehicle at a lower peak time. TOU charging specifically is an established strategy to reduce peak loads; one study found that when charging begins randomly during TOU windows, peak load decreased by 5% (Jones et al. 2022). Table 11 outlines the three primary types of price signal strategies used by utilities to shift EV charging loads to off-peak times.

Table 11. EV Charging Price Signal Strategies Used by Utilities to Move Electricity Load to Off-Peak Times

Price Signal	Description
TOU rates	Different rates for “on-peak” and “off-peak” (and sometimes “mid-peak”) times of the day. Rates typically differ based on season as well.
Demand response rates	Demand response events occur during periods of high load—such as on a hot summer day when there is high air-conditioning use. Electricity rates can be higher during demand response events to encourage utility customers to unplug their vehicles and charge at a later time.
Real-time pricing [a]	Electricity rates adapt dynamically to real-time grid conditions. Generally, real-time pricing has currently only been implemented in pilot programs.

[a] Also known as continuous management (Smart Electric Power Alliance 2021).

Smart Managed Charging Strategies

Charging price signals traditionally rely on the EV owner’s awareness of varying electricity prices. However, there are also smart charging strategies where a controller initiates charging at specified times using utility pricing or even grid conditions as inputs. A selection of smart charging strategies studied by the DOE Charging Infrastructure Technologies: Smart Electric Vehicle Charging for a Reliable and Resilient Grid (RECHARGE) project are included in Table 12.

Table 12. EV Smart Charging Control Strategies and Their Objectives.

Adapted from Bennett, Lave, and Scofield (2021).

Controlled Charging Strategy	Description
TOU Random	Decentralized controller initiates charging randomly within vehicle dwell and TOU windows
Random Start	Decentralized controller initiates charging randomly within vehicle dwell times
Peak Avoidance	Centralized controller initiates charging at a time that minimizes feeder peak
Volt/VAR	Decentralized controller provides reactive power support based on local power quality
Volt/Watt	Decentralized controller shifts EV charging real power within vehicle dwell window to reduce grid voltage concerns
BTM/DER	Decentralized controller shifts EV charging within vehicle dwell window to reduce behind-the-meter peak demand

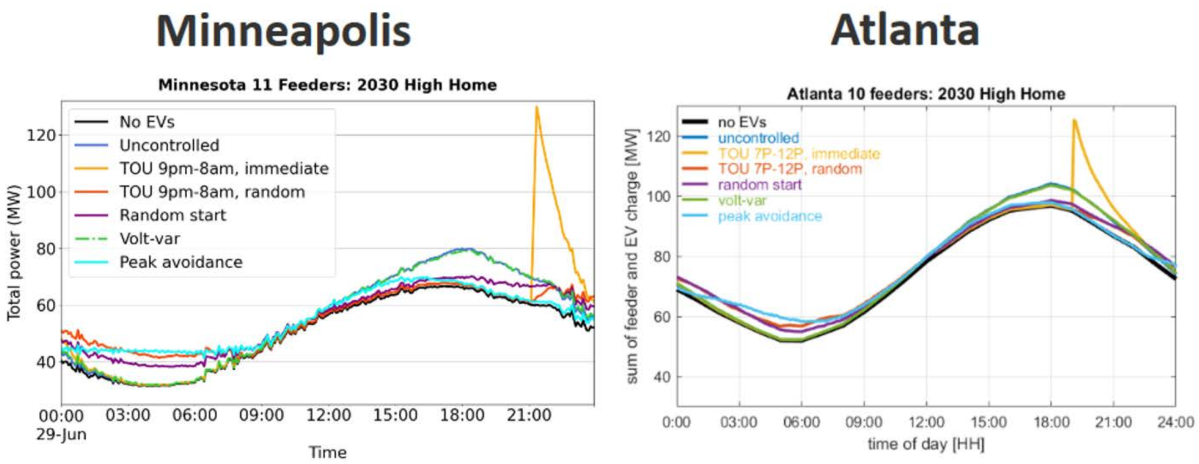
The DOE RECHARGE project found that many of these smart charging strategies—which distribute the charging load within a vehicle’s “dwell period” (i.e., while parked)—reduce the impact of large-scale EV adoption on the grid. RECHARGE is investigating the grid impacts of approximately 15% of light-duty EV adoptions in the Minneapolis and Atlanta regions and proposes smart charge management solutions to mitigate those impacts (Bennett, Lave, and

Scofield 2021). The project findings suggest that modest adoption of light-duty EVs (about 15%–20%) primarily using AC Level 2 to charge will have little impact on the grid. High-power stations such as public fast chargers (DCFCs) or medium- and heavy-duty charging depots with greater than 5-MW interconnection needs per site will be most heavily impacted.

Figure 15 from the RECHARGE findings show the feeder power over time for different modeled smart charge control strategies in Minneapolis and Atlanta.

2030 High Home

Region	Total EV Count	% EV Adoption*
Minn.	11,187	53%
Atlanta	5,974	30%



2030 High Work

Region	Total EV Count	EVs/Customer*
Minn.	9,987	42%
Atlanta	7,495	22%

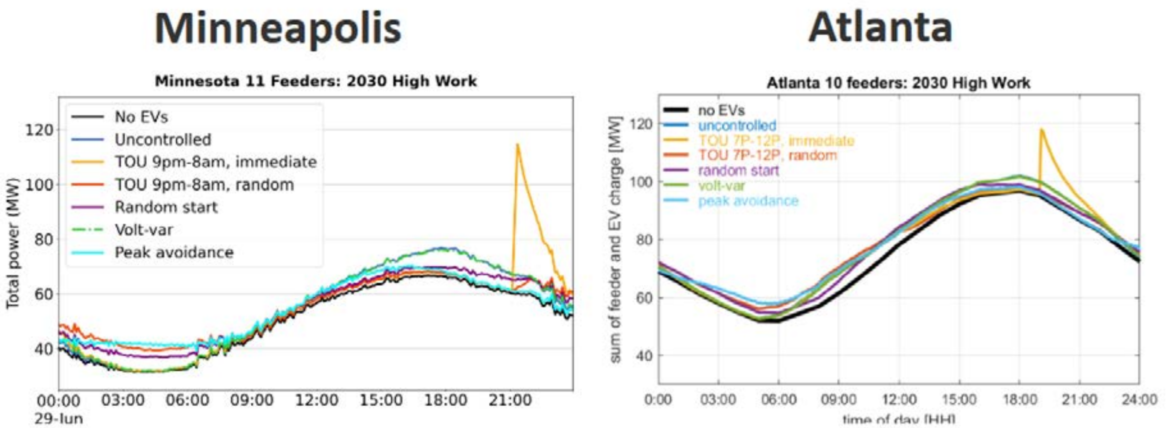


Figure 15. RECHARGE project modeling results showing feeder power over time under various smart charging scenarios in Minneapolis and Atlanta.

Source: Bennett, Lave, and Scofield (2021).

Another DOE project—Flexible charging to Unify the grid and transportation Sectors for EVs at scale (FUSE), part of the Electric Vehicles at Scale (EVs@Scale) Lab Consortium—aims to develop an adaptive ecosystem of smart charge management and vehicle–grid integration strategies and tools to reduce barriers to electrification (Meintz et al. 2022). The FUSE project is specifically looking at the impacts of charging EVs (including light, medium, and heavy duty) at higher adoption levels (about 50%) throughout Virginia.

An intermediate step toward smart charging involves using stationary battery storage (or other types of energy storage) as a backup charging source, allowing EVs to charge off-grid when needed and avoiding straining the grid during certain times. This still typically requires human intervention to decide when battery storage versus the grid is used unless a controller is programmed and installed.

6.3.1.2 Example Demonstrating the Potential Impact of TOU Rates on BEV Sales

A simplified example using TOU rates can demonstrate the connection between adopting a new electricity rate policy and BEV sales, assuming purchase decisions are made based on economics. However, TOU rates differ based on the utility and location, and can include off-peak, on-peak, and even mid-peak rates that vary based on month, time of day, and day of week. Standard rates also vary based on utility and month but remain the same no matter the time of day. Therefore, we focus on one location for the sake of example: Queen Creek, Arizona, selected due to the innovative residential electricity rate structure options offered by the utility servicing the town.

Residential customers of Queen Creek have a choice between multiple electricity rate plans. One is a standard electricity rate, which stays the same throughout the day (but varies by month) and averages to \$0.5525/kWh on an annual basis. A second option is a TOU rate, with more expensive on-peak rates at certain hours (also varying by month). If all EV charging is assumed to be during off-peak times—which a savvy customer could do through planning to charge their vehicle primarily during nighttime hours—the average TOU off-peak rate is \$0.0895/kWh. Assuming the linear relationship between change in electricity rates and BEV sales found by Bushnell, Muehlegger, and Rapson (2021), instituting a TOU rate policy (and switching from a standard to TOU off-peak rate) could result in a 0.19% increase in monthly BEV sales. This calculation and the assumptions used are shown in Table 13. For the sake of comparison, a scenario shifting from standard rates to TOU on-peak (assuming all EV charging is during more expensive, on-peak times) is also calculated. Even when charging occurs during on-peak times, average electricity rates are still lower than the standard rate in Queen Creek.

It is important to note that the standard average electricity rate in Queen Creek (\$0.5525/kWh) is more than 4 times the national average due to high electricity rates, at nearly \$1.00/kWh from November through April. If the average standard rate were \$0.13/kWh (roughly the national average [EIA 2023a]), going from charging one's vehicle with the standard rate to the TOU off-peak rate (assuming charging only during off-peak times) would still result in a cheaper rate, but one that is only \$0.0606/kWh cheaper, corresponding to a 0.02% increase in monthly BEV sales.

The utility Salt River Project also has an experimental EV price plan with even lower electricity rates during nighttime hours (11 p.m. to 5 a.m.) (U.S. Utility Rate Database 2023c). The project estimated that customers who charge during these "super off-peak" hours save an average of

8.6% of their electricity bill (based on annual 2021 customer usage) (SRP 2024). This is even cheaper than the TOU off-peak plan and could lead to even higher increases in BEV sales.

Table 13. Simplified Example Estimating the Impact of TOU Rates on BEV Sales in Queen Creek, Arizona [a]

Standard Rate → TOU Off-Peak Scenario	
Standard rate [b]	$0.5525/kWh
TOU rate: off-peak [c]	$0.0895/kWh
Decrease in electricity rate	$0.4630/kWh
Estimated monthly sales increase	According to the linear relationship between electricity rate and monthly BEV sales found by Bushnell, Muehlegger, and Rapson (2021), a $0.548/kWh increase in electricity rate would result in **0.19% higher BEV sales when switching from a standard rate to TOU off-peak**
Standard Rate → TOU On-Peak Scenario	
Standard rate [b]	$0.5525/kWh
TOU rate: on-peak [c]	$0.1500/kWh
Decrease in electricity rate	$0.4024/kWh
Estimated monthly sales increase	According to the linear relationship between electricity rate and monthly BEV sales found by Bushnell, Muehlegger, and Rapson (2021), a $0.4024/kWh increase in electricity rate would result in **0.16% higher BEV sales when switching from a standard rate to TOU on-peak**

[a] Assumes purchase decisions are economically rational. TOU off-peak and TOU on-peak assume all BEV charging occurs during off-peak and on-peak periods, respectively.

[b] Residential basic rates effective as of Nov. 1, 2023, were used (U.S. Utility Rate Database 2023a). Weighted annual average assuming 4,496 kWh/year of vehicle charging (3-mi/kWh efficiency multiplied by 1,124 miles driven per month, from DOE [2024]) spread equally throughout the year, with 70% of charging occurring on weekdays and 30% on weekends.

[c] Residential standard TOU rates effective as of Nov. 1, 2023, were used (U.S. Utility Rate Database 2023b). Weighted annual average assuming 4,496 kWh/year of vehicle charging (3-mi/kWh efficiency multiplied by 1,124 miles driven per month, from DOE [2024]) spread equally throughout the year, with 70% of charging occurring on weekdays and 30% on weekends.

However, it is important to note that TOU rate awareness varies and may not impact EV adoption in the same way that a change in standard electricity rate does, and this is an area of needed future research.

6.3.1.3 Bidirectional Charging Strategies

Bidirectional charging can enable more effective temporal EV load management compared to unidirectional managed charging strategies. Bidirectional charging involves EV charging where the flow of electricity can move both from the grid to the vehicle and from the vehicle to the grid. Electricity from the vehicle can also go to other sources besides the electric grid, such as a home battery storage system or to power critical loads. This has even more value to the grid than unidirectional managed charging strategies because charged EV batteries can be used as a grid resource. With bidirectional charging (also known as vehicle-to-grid), the plugged-in vehicles could be treated as battery storage, with an integrated controller ensuring that vehicles are fully charged by the date and time the EV owners specified. The EV owners could also be compensated for allowing this grid interaction; an example of this could be parked, plugged-in

EVs at an airport (that do not need to be fully charged until the EV owner returns from a trip). In another example, by purchasing electricity during off-peak times and selling it back during peak times, an EV owner could turn bidirectional charging into an income stream. It is possible that these innovative income streams could reduce the total cost of EV ownership and encourage greater EV adoption. Bidirectional charging can also enable renewables by adding flexibility to resources that are not available on-demand and may be especially needed in microgrid and islanded situations.

Bidirectional charging is currently in pilot phases. The primary challenges are related to policy, rate-setting logistics, and communication between various stakeholders—namely the EV owner, property owner, and utility.

6.3.2 Geospatial EV Load Management

In addition to grid loads varying over the course of a day, peak loads and grid capacity also vary based on grid location. For example, some feeders or substations are already near capacity and would therefore require costly upgrades if their peak load increased from EVs. Conversely, other feeders or substations are under capacity and would therefore be relatively inexpensive to accommodate additional peak loads from EVs. Utilities can perform a "hosting capacity analysis" to help determine the location-specific upgrade needs of additional EVs, as done in Paudyal et al. (2021). Heat map results from Paudyal et al. (2021) showing the available EV hosting capacity on a feeder in Minnesota are shown in Figure 16 as an example.

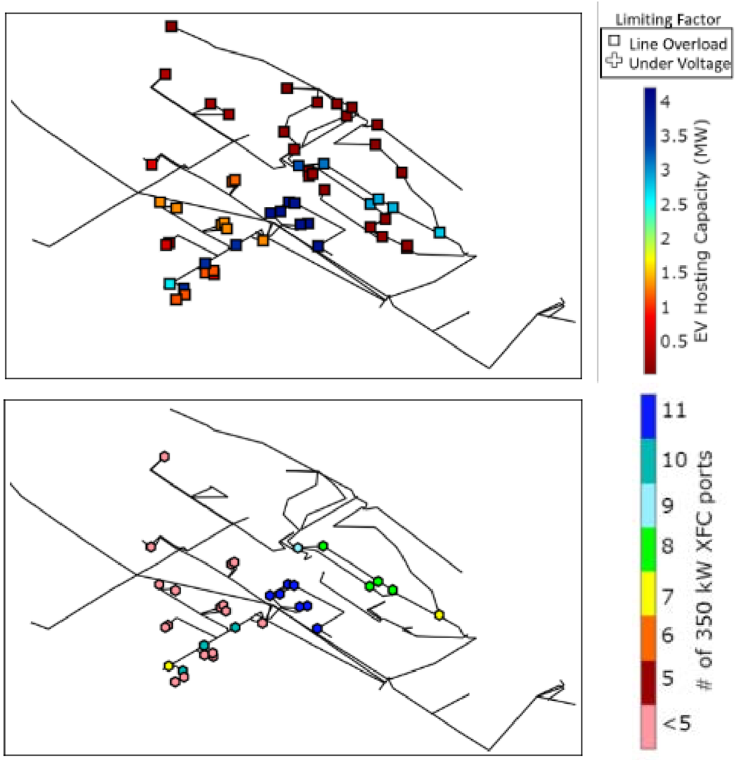


Figure 16. Heat map of a feeder in Minnesota showing the available EV hosting capacity of nodes (top) and number of 350-kW charging ports the nodes can support (bottom).

Minnesota feeder shown is approximately 6 km long. Note: XFC = extreme fast charging (DCFC capable of 350 kW and above). Source: Paudyal et al. (2021).

Depending on the location of EVSE, there are some grid upgrades that will be required to support large-scale EV adoption. Two examples are upgrading distribution transformers to support distributed residential charging and substation capacity upgrades to support higher-power charging sites (where distributed grids are unable to support).

6.4 Impact of EV Charging Speed and EV Size on the Grid

Faster, more powerful EVSE multiplies both the negative and positive impacts that EVSE can have on the grid. For example, one 350-kW charger has the same impact on the grid as 35 simultaneously operational 10-kW chargers. However, the 350-kW charger is not going to be spread between different feeders or substations the way that 35 10-kW chargers would be. Another difference is that the single 350-kW charger should be easier to manage because there is only one point of control. Despite this, the most powerful EVSE tends to be the least flexible and therefore the least compatible with charge management schemes. This is because the most powerful EVSE is used in applications where time is a constrained factor. Therefore, customers using fast EVSE have not scheduled time for a slower charge or a postponement of their charge imposed for grid purposes.

In addition, EVSE does not continuously operate at its rated power output, and EV charging speeds vary if power sharing between neighboring chargers is enabled. These are considerations of EVSE that may be impacted as charging speeds continue to increase. DCFCs have peak power ratings as well as continuous power ratings. For example, ABB's Terra HP 350 fast chargers are rated at 350 kW for peak power and 320 kW for continuous power. In practice, EVs only charge at their highest power for a short period of the time they are plugged in. For example, in a test performed by *InsideEVs*, two Tesla Model 3 EVs reached their maximum power of 250 kW only when the battery was between approximately 10% and 25% charged, with variation based on model year, as shown in Figure 17 (Moloughney 2021).

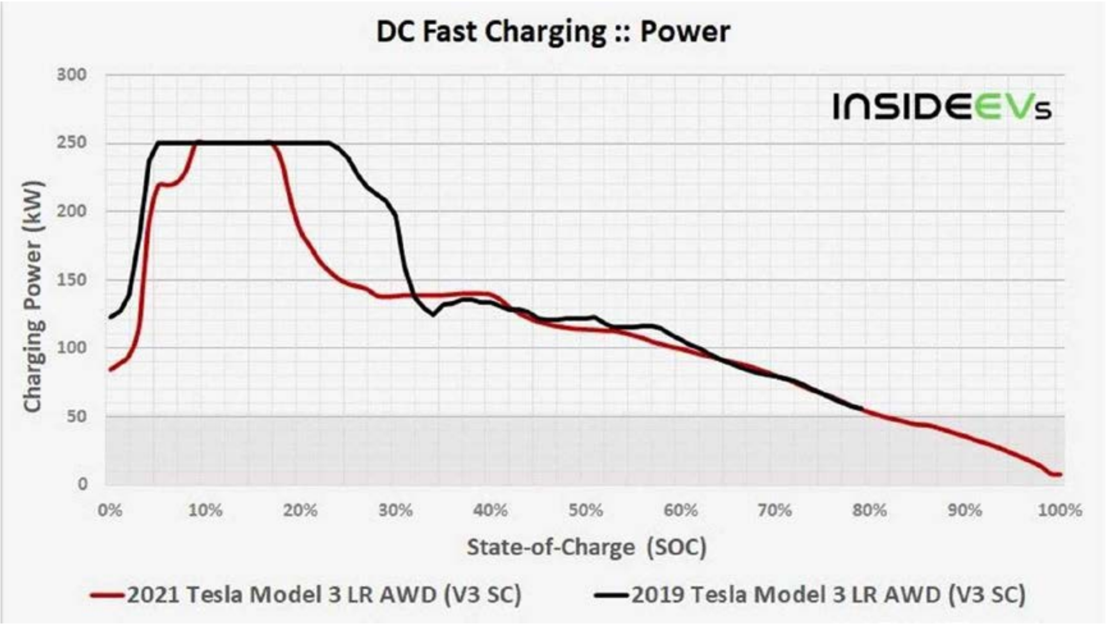


Figure 17. Charging power vs. battery state of charge in a test performed by *InsideEVs*.

Source: Moloughney (2021).

The supporting grid still needs to support these high EVSE loads even if they are only for part of the total EV charge time. If EVSE and supporting infrastructure are not sized and/or managed appropriately, charging speed can decrease with high utilization, or charging can fail completely. If power sharing among chargers is enabled, the output power of a charging station with multiple chargers is capped. For example, a station with 10 chargers that are all being used at the same time will charge each of the 10 vehicles slower than it would if only 2 vehicles were charging. EVSE with higher charging speeds therefore have higher power demands that need to be planned for carefully to avoid slower-than-anticipated charging speeds.

Challenges with larger EVs extend beyond electrical equipment. Accessing a charging station while driving a larger EV (particularly medium/heavy duty vehicles) can present issues such as parking spaces not being large enough for the vehicle to physically fit, or there not being enough space for the vehicle to wait for a charger to become available. Medium- and heavy-duty vehicles also have greater power requirements than light-duty vehicles that can impact the grid more severely. A forthcoming NREL report on medium- and heavy-duty vehicles will delve into more specific power and charging station requirements for these large vehicles with unique charging needs.

7 Conclusion

Public EVSE reliability in the United States is currently low, with top causes of no-charge events including broken components, connectivity and communication issues, payment system failures, and power source failures. In addition, the ratio of EV stock to public charging stations is lower in the United States than in more developed markets, indicating that greater EVSE availability is needed. Issues with public charging stations are consistently found to be the top reasons that potential EV buyers do not purchase an EV, demonstrating that both EVSE reliability and availability impacts EV adoption. As recent funding initiatives result in an expansion of public chargers across the United States, as well as an increase in the uptime of existing chargers, EV adoption will likely grow.

This report explored multiple parameters that impact EVSE reliability and deployment, which in turn impact EV sales. These include extreme weather, codes and standards, region (urban vs. rural), and grid network type. Grid reliability was not found to impact EV adoption, but EVSE can provide both benefits and challenges to the power grid, and managed charging strategies will be key as EV adoption grows. It is important to note that managed charging strategies (including smart charging) depend on EV owners opting into these programs. A recent University of Texas at Austin survey of 1,000 people in the United States found that roughly 25% would not participate in any kind of smart charging strategy (Dean and Kockelman 2023).

There are multiple areas for future work. First, the sample groups for most studies and surveys investigating the relationship between EVSE and EV adoption (as outlined in Section 3.1) favor people who are open to purchasing an EV. Further research should include surveys of people that do not drive or want to drive an EV to see how charging infrastructure is impacting their decision. Second, Section 5.3 attempts to quantify the impact of outdoor temperature on EV sales, focusing on higher charging needs in extreme hot and cold environments resulting in more expensive charging sessions. However, there are other temperature-related factors that impact EV sales, including battery degradation, reduced (real or perceived) reliability of vehicle charging, or avoidance of human exposure to extreme temperatures. Future work will need to better control for these—and other—parameters to more accurately define the relationship between outdoor temperature and EV sales. Similarly, Section 6.3 estimates the impact of electricity rate changes on monthly EV sales. Differences between the impact of TOU rate changes and standard rate changes on monthly EV sales need to be better studied. In addition, the potential relationship between grid reliability and EV stock share could be further investigated, building from Section 5.4. For example, the state-by-state analysis shown in Figure 11 could be repeated with the y-axis showing EV stock share for only high-income households, rather than overall EV stock share. This would investigate the relationship between EV adoption and grid reliability only for households that are most likely to purchase an EV. In addition, the relationship between grid reliability and EV sales (rather than EV stock) could be investigated.

References

AFDC. 2023a. “Alternative Fueling Station Locator.” AFDC. October 18, 2023. https://afdc.energy.gov/stations/.

———. 2023b. “Charging Infrastructure Operation and Maintenance.” October 20, 2023. https://afdc.energy.gov/fuels/electricity_infrastructure_maintenance_and_operation.html.

———. 2024. “Vehicle Registration Counts by State.” March 26, 2024. https://afdc.energy.gov/vehicle-registration.

Anwar, Muhammad Bashar, Matteo Muratori, Paige Jadun, Elaine Hale, Brian Bush, Paul Denholm, Ookie Ma, and Kara Podkaminer. 2022. “Assessing the Value of Electric Vehicle Managed Charging: A Review of Methodologies and Results.” *Energy & Environmental Science* 15 (2): 466–98. https://doi.org/10.1039/D1EE02206G.

Argue, Charlotte. 2023. “To What Degree Does Temperature Impact EV Range?” Geotab. February 6, 2023. https://www.geotab.com/blog/ev-range/.

Baatar, Bilegt, Kassidy Heckmann, Tiffany Hoang, Ruby Jarvis, and Priya Sakhiya. 2019. “Preparing Rural America for the Electric Vehicle Revolution.” UC Davis: Center for American Progress.

Barry, Keith, and Jeff S. Bartlett. 2024. “Automakers Move to a Common Plug Standard to Allow Their EVs to Use Tesla Superchargers.” Consumer Reports. February 29, 2024. https://www.consumerreports.org/cars/hybrids-evs/tesla-superchargers-open-to-other-evs-what-to-know-a9262067544/.

Bartlett, Jeff. 2022. “More Americans Would Buy an Electric Vehicle, and Some Consumers Would Use Low-Carbon Fuels, Survey Shows.” Consumer Reports. July 7, 2022. https://www.consumerreports.org/cars/hybrids-evs/interest-in-electric-vehicles-and-low-carbon-fuels-survey-a8457332578/.

Bennett, Jesse, and Cabell Hodge. 2020. “Federal Workplace Charging Program Guide.” DOE/GO-102020-5442. https://www.energy.gov/sites/default/files/2020/11/f80/federal-workplace-charging-guide.pdf.

Bennett, Jesse, Matt Lave, and Don Scofield. 2021. “Charging Infrastructure Technologies: Smart Electric Vehicle Charging for a Reliable and Resilient Grid (RECHARGE).” Presented at the DOE Vehicle Technologies Program 2021 Annual Merit Review and Peer Evaluation Meeting, June 23. https://www.energy.gov/sites/default/files/2021-06/elt202_bennett_2021_o_5-14_752pm_KS_TM.pdf.

Bopp, Kaylyn, Jesse Bennett, and Nathan Lee. 2020. “Electric Vehicle Supply Equipment: An Overview of Technical Standards to Support Lao PDR Electric Vehicle Market Development.” NREL/PR-7A40-78085. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy21osti/78085.pdf.

Borlaug, Brennan, Matteo Muratori, Madeline Gilleran, David Woody, William Muston, Thomas Canada, Andrew Ingram, Hal Gresham, and Charlie McQueen. 2021. “Heavy-Duty Truck Electrification and the Impacts of Depot Charging on Electricity Distribution Systems.” *Nature Energy* 6 (6): 673–82. https://doi.org/10.1038/s41560-021-00855-0.

Brooker, Aaron, Jeffrey Gonder, Sean Lopp, and Jacob Ward. 2015. “ADOPT: A Historically Validated Light Duty Vehicle Consumer Choice Model.” In *SAE 2015 World Congress & Exhibition*, 2015-01–0974. https://doi.org/10.4271/2015-01-0974.

Bushnell, James, Erich Muehlegger, and David Rapson. 2021. “Do Electricity Prices Affect Electric Vehicle Adoption?” Institute of Transportation Studies. https://escholarship.org/uc/item/7p19k8c6.

Butler, Josh. 2023. "Sales of Electric Vehicles Surge as Fast-Charging Sites Double across Australia in a Year." *The Guardian*, December 22, 2023, sec. Environment. https://www.theguardian.com/environment/2023/dec/23/ev-electric-vehicles-sales-rise-australia-government-strategies.

California Air Resources Board. 2022. "Electric Vehicle Supply Equipment Standards Technology Review," February.

California Energy Commission. 2018. "Electric Vehicle Charger Selection Guide." U.S. Department of Energy Alternative Fuels Data Center. https://afdc.energy.gov/files/u/publication/EV_Charger_Selection_Guide_2018-01-112.pdf.

CHAdeMO. 2023. "FAQ: CHAdeMO Association & Membership." October 17, 2023. https://www.chademo.com/faq.

———. 2024. "Comemso EV Charging Analyzer." CHAdeMO. January 4, 2024. https://www.chademo.com/products/other/comemso.

ChargerHelp! 2023. "ChargerHelp! EV Charger Repair." 2023. https://www.chargerhelp.com.

ChargeX Consortium. 2023. "Minimum Required Error Codes by ChargeX." Idaho National Laboratory. September 2023. https://inl.gov/chargex/mrec/.

Climate Central. 2022. "Surging Power Outages and Climate Change." https://assets.ctfassets.net/cxgxgstp8r5d/73igUswSfOhdo7DUDVLwK7/bb0a4e95e1d04457e56106355a1f74b9/2022PowerOutages.pdf.

Consumer Reports. 2022a. "Battery Electric Vehicles and Low Carbon Fuel: A Nationally Representative Multi-Mode Survey." https://article.images.consumerreports.org/prod/content/dam/surveys/Consumer_Reports_BEV%20AND%20LCF%20SURVEY_18_FEBRUARY_2022.

———. 2022b. "Electric Vehicle Owners: A Nationally Representative Multi-Mode Survey." https://article.images.consumerreports.org/image/upload/v1679253682/prod/content/dam/surveys/Consumer_Reports_EV_Owners_October_November_2022.pdf.

Cox Automotive. 2023. "Path to EV Adoption: Consumer and Dealer Perspectives." https://www.coxautoinc.com/wp-content/uploads/2023/06/Path-to-EV-Adoption-Study-Summary-June-2023.pdf.

Crothers, Brooke. 2023. "Electrify America Explains Cause Of Those Vexing EV Charging Problems." *Forbes*, October 15, 2023, sec. Consumer Tech. https://www.forbes.com/sites/brookecrothers/2023/10/15/electrify-america-explains-cause-of-those-vexing-ev-charging-problems/.

Dean, Matthew D., and Kara M. Kockelman. 2023. "Americans' Opinions and Interests in Plug-in Electric Vehicle Smart Charging Programs." *Transportation Research Part D: Transport and Environment* 129:104129.

Deloitte. 2023. "2023 Global Automotive Consumer Study." January 2023. https://www2.deloitte.com/us/en/pages/consumer-business/articles/global-automotive-consumer-study.html.

Do, Vivian, Heather McBrien, Nina M. Flores, Alexander J. Northrop, Jeffrey Schlegelmilch, Mathew V. Kiang, and Joan A. Casey. 2023. "Spatiotemporal Distribution of Power Outages with Climate Events and Social Vulnerability in the USA." *Nature Communications* 14 (1): 2470. https://doi.org/10.1038/s41467-023-38084-6.

DOE. 2024. "The Cost to Charge an Electric Vehicle Explained." Energy.Gov. 2024. https://www.energy.gov/energysaver/cost-charge-electric-vehicle-explained.

eCFR. 2023. “23 CFR Part 680 -- National Electric Vehicle Infrastructure Standards and Requirements.” June 5, 2023. https://www.ecfr.gov/current/title-23/part-680.

Egnér, Filippa, and Lina Trosvik. 2018. “Electric Vehicle Adoption in Sweden and the Impact of Local Policy Instruments.” *Energy Policy* 121 (October):584–96. https://doi.org/10.1016/j.enpol.2018.06.040.

EIA. 2022. “Transportation Demand Module.” EIA. https://www.eia.gov/outlooks/aeo/assumptions/pdf/transportation.pdf.

———. 2023a. “Annual Energy Outlook 2023.” March 16, 2023. https://www.eia.gov/outlooks/aeo/narrative/index.php.

———. 2023b. “Electric Power Annual.” October 19, 2023. https://www.eia.gov/electricity/annual/.

———. 2023c. “US Electricity Profile 2022.” EIA. 2023. https://www.eia.gov/electricity/state/.

———. 2024. “Electricity Data - U.S. Energy Information Administration (EIA).” 2024. https://www.eia.gov/electricity/data.php.

Eichberger, John, Jeff Hove, Marjorie Kass, and Amanda Patterson. 2023. “Consumer Survey: Driving Behavior and Alternative Vehicles.” Transportation Energy Institute. https://www.transportationenergy.org/wp-content/uploads/2023/06/Consumer-Survey-Driving-Behavior-and-Alternative-Vehicles_FINAL.pdf.

EPA. 2020. “Plug-in Electric Vehicle Charging.” Other Policies and Guidance. September 16, 2020. https://www.epa.gov/greenvehicles/plug-electric-vehicle-charging.

EVDB. 2023. “NZ EV Market Share: New Cars.” EVDB. January 17, 2023. https://evdb.nz/ev-new-cars.

Farley, Rendall, Mike Vervair, and Jon Czerniak. 2019. “Electric Vehicle Supply Equipment Pilot Final Report.” Avista Corp. https://www.myavista.com/energy-savings/electric-transportation.

FEMA. 2023. “Data Resources - National Risk Index.” FEMA. 2023. https://hazards.fema.gov/nri/data-resources#hdrDownload.

———. 2024a. “National Risk Index - Annualized Frequency.” FEMA. 2024. https://hazards.fema.gov/nri/annualized-frequency.

———. 2024b. “National Risk Index - Map.” FEMA. 2024. https://hazards.fema.gov/nri/map.

Fernández, Julián A., Omar E. Herrera, and Walter Mérida. 2020. “Impact of an Electrified Parkade on the Built Environment: An Unsupervised Learning Approach.” *Transportation Research Part D: Transport and Environment* 78 (January):102199. https://doi.org/10.1016/j.trd.2019.12.001.

Ferris, David. 2023. “Why America’s EV Chargers Keep Breaking.” POLITICO. April 12, 2023. https://www.politico.com/news/2023/04/12/america-ev-chargers-keep-breaking-heres-why-00089181.

FHWA. 2023a. “Biden-Harris Administration Making $100 Million Available to Improve EV Charger Reliability.” September 13, 2023. https://highways.dot.gov/newsroom/biden-harris-administration-making-100-million-available-improve-ev-charger-reliability.

———. 2023b. “National Electric Vehicle Infrastructure Standards and Requirements.” Federal Register. February 28, 2023. https://www.federalregister.gov/documents/2023/02/28/2023-03500/national-electric-vehicle-infrastructure-standards-and-requirements.

———. n.d. “Table HM-44: National Highway System Travel (2021), Annual Vehicle-Miles by Functional System.” Highway Statistics 2021. Accessed February 2, 2024. https://www.fhwa.dot.gov/policyinformation/statistics/2021/hm44.cfm.

Ghasri, Milad, Ali Ardeshiri, and Taha Rashidi. 2019. “Perception towards Electric Vehicles and the Impact on Consumers’ Preference.” *Transportation Research Part D: Transport and Environment* 77 (December):271–91. https://doi.org/10.1016/j.trd.2019.11.003.

Golden, Mark. 2022. “Charging Cars Needs to Move from Nighttime at Home to Daytime at Work, Stanford Study Finds,” September 22, 2022. https://energy.stanford.edu/news/charging-cars-needs-move-nighttime-home-daytime-work-stanford-study-finds.

Greene, David L., Eleftheria Kontou, Brennan Borlaug, Aaron Brooker, and Matteo Muratori. 2020. “Public Charging Infrastructure for Plug-in Electric Vehicles: What Is It Worth?” *Transportation Research Part D: Transport and Environment* 78 (January):102182. https://doi.org/10.1016/j.trd.2019.11.011.

Greene, David, Matteo Muratori, Eleftheria Kontou, Brennan Borlaug, Marc Melaina, and Aaron Brooker. 2020. “Quantifying the Tangible Value of Public Electric Vehicle Charging Infrastructure.” NREL/TP-5400-70340, 1829680, MainId:6940. https://doi.org/10.2172/1829680.

Hardman, Scott, and Gil Tal. 2021. “Understanding Discontinuance among California’s Electric Vehicle Owners.” *Nature Energy* 6 (5): 538–45. https://doi.org/10.1038/s41560-021-00814-9.

IEA. 2022. “Trends in Charging Infrastructure – Global EV Outlook 2022 – Analysis.” IEA. 2022. https://www.iea.org/reports/global-ev-outlook-2022/trends-in-charging-infrastructure.

———. 2023a. “Executive Summary – Global EV Outlook 2023 – Analysis.” IEA. 2023. https://www.iea.org/reports/global-ev-outlook-2023/executive-summary.

———. 2023b. “Global EV Outlook 2023.” IEA. April 2023. https://www.iea.org/data-and-statistics/data-product/global-ev-outlook-2023.

———. 2023c. “Trends in Charging Infrastructure – Global EV Outlook 2023 – Analysis.” IEA. 2023. https://www.iea.org/reports/global-ev-outlook-2023/trends-in-charging-infrastructure.

IEC. 2017. “IEC 61851-1:2017: Electric Vehicle Conductive Charging System - Part 1: General Requirements.” https://webstore.iec.ch/publication/33644.

Income Power. 2023a. “EV Maintenance Service and Warranty Work.” March 21, 2023. https://www.incomepowerllc.com/services/ev-maintenance-service-and-warranty-work/.

———. 2023b. “Our Work.” Income Power. March 21, 2023. https://www.incomepowerllc.com/our-work/.

Jackson, Nicole, Andrea Staid, Jean-Paul Watson, Hiba Baroud, and Jin-Zhu Yu. 2021. “Characterization of Extreme Weather Events during Large-Scale Power Outages.” In *Proposed for Presentation at the Society for Risk Analysis Annual Meeting Held December 6-10, 2021*. DOE. https://doi.org/10.2172/2001583.

J.D. Power. 2023. “2023 U.S. Electric Vehicle Experience (EVX) Public Charging Study.” J.D. Power. August 16, 2023. https://www.jdpower.com/business/press-releases/2023-us-electric-vehicle-experience-evx-public-charging-study.

———. 2024. "2024 U.S. Electric Vehicle Experience (EVX) Ownership Study." J.D. Power. February 27, 2024. https://www.jdpower.com/business/press-releases/2024-us-electric-vehicle-experience-evx-ownership-study.

Joint Office of Energy and Transportation. 2023. "National Charging Experience Consortium." May 18, 2023. https://driveelectric.gov/chargex-consortium.

Jones, C. Birk, Matthew Lave, William Vining, and Brooke Marshall Garcia. 2021. "Uncontrolled Electric Vehicle Charging Impacts on Distribution Electric Power Systems with Primarily Residential, Commercial or Industrial Loads." *Energies* 14 (6): 1688. https://doi.org/10.3390/en14061688.

Jones, C. Birk, William Vining, Matthew Lave, Thad Haines, Christopher Neuman, Jesse Bennett, and Don R. Scoffield. 2022. "Impact of Electric Vehicle Customer Response to Time-of-Use Rates on Distribution Power Grids." *Energy Reports* 8 (November). https://doi.org/10.1016/j.egyr.2022.06.048.

Karanam, Vaishnavi, and Gil Tal. 2023. "How Disruptive Are Unreliable Electric Vehicle Chargers? Empirically Evaluating the Impact of Charger Reliability on Driver Experience." *Research Square*, March. https://doi.org/10.21203/rs.3.rs-2592351/v1.

Keith, David, and Jim Womack. 2023. "Building and Sustaining Reliable Public EV Charging in the United States." *Environmental Research Letters* 18 (1): 011004. https://doi.org/10.1088/1748-9326/acae39.

Kevala. 2023. "CPUC Electrification Impacts Study Part 1: Bottom-Up Load Forecasting and System-Level Electrification Impacts Cost Estimates - Kevala." 2023. https://www.kevala.com/resources/electrification-impacts-study-part-1.

Koncar, Ilija, and I. Safak Bayram. 2021. "A Probabilistic Methodology to Quantify the Impacts of Cold Weather on Electric Vehicle Demand: A Case Study in the U.K." *IEEE Access* 9:88205–16. https://doi.org/10.1109/ACCESS.2021.3090534.

Ledna, Catherine, Matteo Muratori, Aaron Brooker, Eric Wood, and David Greene. 2022. "How to Support EV Adoption: Tradeoffs between Charging Infrastructure Investments and Vehicle Subsidies in California." *Energy Policy* 165 (June):112931. https://doi.org/10.1016/j.enpol.2022.112931.

Lienert, Paul, and David Gregorio. 2023. "Big Investors Spur Consolidation, Growth in EV Charging Sector." *Reuters*, December 12, 2023, sec. Autos & Transportation. https://www.reuters.com/business/autos-transportation/big-investors-spur-consolidation-growth-ev-charging-sector-2023-12-13/.

Lommele, Stephen, Ranjit R. Desai, Caley Johnson, Amy Snelling, Abby Brown, Mark Singer, Jesse Bennett, Jeff Cappellucci, Johanna Levene, and Christopher Hoehne. forthcoming. "Assessment of Alternative Fueling Infrastructure in the United States." National Renewable Energy Laboratory.

Lutz, Hannah. 2023. "Wanted: Electricians to Fix Thousands of Broken EV Chargers." Automotive News. October 9, 2023. https://www.autonews.com/mobility-report/broken-ev-chargers-need-more-certified-technicians.

Malarkey, Daniel, Rubina Singh, and Don MacKenzie. 2023. "Customer Experience at Public Charging Stations and Its Effects on the Purchase and Use of Electric Vehicles." INL/RPT-23-74951. ChargeX Consortium. https://inl.gov/content/uploads/2023/07/Customer-Experience-at-Public-Charging-Stations_INLRPT-23-74951_12-12-23.pdf.

McCormick, Robert, and Kristi Moriarty. 2023. “Biodiesel Handling and Use Guide: Sixth Edition.” NREL/TP--4A00-86939, CRD-15-00593, 2001221. https://doi.org/10.2172/2001221.

Meintz, Andrew, Jesse Bennett, Brennan Borlaug, Zhaocai Liu, Mingzhi Zhang, Christian Birk Jones, Shibani Ghosh, et al. 2022. “EVs@Scale Deep Dive - SCM/VGI (Day 1: SCM/VGI Analysis).” NREL/PR-5400-84273. National Renewable Energy Lab. (NREL), Golden, CO (United States). https://www.osti.gov/biblio/1894865.

Meintz, Andrew, John Kisacikoglu, Sam Thurston, Barney Carlson, Michael Starke, Thomas Carroll, Jesse Bennett, et al. 2023. “EVs@Scale Lab Consortium Semi-Annual Stakeholder Meeting.” https://www.nrel.gov/docs/fy24osti/87781.pdf.

Meintz, Andrew, Lee Slezak, Sam Thurston, Barney Carlson, Alastair Thurlbeck, John Kisacikoglu, Prasad Kandula, et al. 2023. “Electric Vehicles at Scale (EVs@Scale) Laboratory Consortium Deep-Dive Technical Meetings: High Power Charging (HPC) Summary Report.” https://research-hub.nrel.gov/en/publications/electric-vehicles-at-scale-evsscale-laboratory-consortium-deep-di-2.

Miele, Amy, Jonn Axsen, Michael Wolinetz, Elicia Maine, and Zoe Long. 2020. “The Role of Charging and Refuelling Infrastructure in Supporting Zero-Emission Vehicle Sales.” *Transportation Research Part D: Transport and Environment* 81 (April):102275. https://doi.org/10.1016/j.trd.2020.102275.

Miller, Brandon. 2023. “HERE and SBD Partner to Provide an In-Depth Analysis of EV Infrastructure in the US and Europe.” SBD Automotive. September 7, 2023. https://www.sbdautomotive.com/post/new-index-identifies-ev-leaders-and-laggards-in-the-u-s-and-europe.

Moloughney, Tom. 2021. “How Fast Does A 2021 Tesla Model 3 Charge? We Find Out.” InsideEVs. 2021. https://insideevs.com/news/506520/tesla-model-3-supercharger-test/.

Moriarty, Kristi, and John Smart. 2024. “Best Practices for Payment Systems at Public Electric Vehicle Charging Stations.” NREL/TP-5400-88821, 2319201, MainId:89600. https://doi.org/10.2172/2319201.

Moye, Brittany. 2023. “EV Consumer Sentiment Survey.” AAA Newsroom. November 20, 2023. https://newsroom.aaa.com/2023/11/annual-electric-vehicle-sentiment-survey/.

Muratori, Matteo. 2018. “Impact of Uncoordinated Plug-in Electric Vehicle Charging on Residential Power Demand.” *Nature Energy* 3 (3): 193–201. https://doi.org/10.1038/s41560-017-0074-z.

Muratori, Matteo, David Greene, Eleftheria Kontou, and Jing Dong. 2020. “The Role of Infrastructure to Enable and Support Electric Drive Vehicles: A Transportation Research Part D Special Issue.” *Transportation Research Part D: Transport and Environment* 89 (December):102609. https://doi.org/10.1016/j.trd.2020.102609.

Narassimhan, Easwaran, and Caley Johnson. 2018. “The Role of Demand-Side Incentives and Charging Infrastructure on Plug-in Electric Vehicle Adoption: Analysis of US States.” *Environmental Research Letters* 13 (7): 074032. https://doi.org/10.1088/1748-9326/aad0f8.

National Grid and Hitachi Energy. 2021. “The Road to Transportation Decarbonization: Understanding Grid Impacts of Electric Fleets.” https://www.nationalgridus.com/media/pdfs/microsites/ev-fleet-program/understandinggridimpactsofelectricfleets.pdf.

National Household Travel Survey. 2022. "2022 National Household Travel Survey (NHTS): Average Vehicle Trip Length." 2022. https://nhts.ornl.gov/de/work/170690977030.html.

Newburger, Emma. 2023. "Nearly Half of Americans Say It's Unlikely They'll Buy an Electric Vehicle as Their next Car: Poll." CNBC. April 11, 2023. https://www.cnbc.com/2023/04/11/nearly-half-of-americans-say-its-unlikely-theyll-buy-an-ev-next-poll.html.

O'Connor, Pete, Ingrid Malmgren, and Lindsey Perkins. 2023. "2023 EV Driver Survey." Los Angeles, CA: Plug In America. https://pluginamerica.org/wp-content/uploads/2023/05/2023-EV-Survey-Final.pdf.

Paudyal, Priti, Shibani Ghosh, Santosh Veda, Deepak Tiwari, and Jal Desai. 2021. "EV Hosting Capacity Analysis on Distribution Grids." In *2021 IEEE Power & Energy Society General Meeting (PESGM)*, 1–5. https://doi.org/10.1109/PESGM46819.2021.9638170.

Plug In America. 2023a. "2023 EV Driver Survey: A Strong Year for EVs, But Charging Reliability Needs Improvement." Plug In America. http://pluginamerica.org/wp-content/uploads/2023/05/2023-EV-Survey-Final.pdf.

———. 2023b. "How Do Consumers Feel about Their EV Charging Experience?" October. https://pluginamerica.org/wp-content/uploads/2023/10/2023.10-Charging-Survey-Analysis.pdf.

Powell, Aaron, Patrick Doyle, Gerry Feldmeier, and Brad Juhasz. 2023. "EV Charging Network Connectivity Basics." Eaton.

Powell, Siobhan, Gustavo Vianna Cezar, Liang Min, Inês M. L. Azevedo, and Ram Rajagopal. 2022. "Charging Infrastructure Access and Operation to Reduce the Grid Impacts of Deep Electric Vehicle Adoption." *Nature Energy* 7 (10): 932–45. https://doi.org/10.1038/s41560-022-01105-7.

Qmerit Electrification Institute. 2023. "Electrification 2030." https://qmerit.com/electrification-2030/.

Quinn, Casey W., Sarah Cardinali, Jason Clifford, Kaleb Houck, Kristi Moriarty, Mayuresh Savargaonkar, John G. Smart, David Estes Smith, and Benny J. Varghese. 2024. "Customer-Focused Key Performance Indicators for Electric Vehicle Charging." INL/RPT-24-77388-Rev000. Idaho National Laboratory (INL), Idaho Falls, ID (United States). https://doi.org/10.2172/2377347.

Recurrent. 2023. "Study: Winter & Cold Weather EV Range Loss in 10,000+ Cars." Recurrent. November 15, 2023. https://www.recurrentauto.com/research/winter-ev-range-loss#:~:text=Cold%20temperatures%20inhibit%20chemical%20reactions,the%20driver%20and%20passengers%20warm.

Rempel, David, Carleen Cullen, Mary Matteson Bryan, and Gustavo Vianna Cezar. 2022. "Reliability of Open Public Electric Vehicle Direct Current Fast Chargers." https://evadoption.com/wp-content/uploads/2022/05/Cool-the-Earth-UCB-study.pdf.

Rodney, McGee. 2023. "SAE J3400 and the Game-Changing Advances in AC Charging." SAE International. December 19, 2023. https://www.sae.org/site/blog/j3400-NACS-standard-rodney-mcgee.

Roper, Preston. 2019. "Electric Vehicle-Grid Integration Spurs Faster Development." *Natural Gas & Electricity* 35 (8): 1–7. https://doi.org/10.1002/gas.22107.

SAE International. 2017. "SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler J1772_201710." October 13, 2017. https://www.sae.org/standards/content/j1772_201710/.

———. 2024. “J3400 (WIP) North American Charging System (NACS) for Electric Vehicles.” March 13, 2024. https://www.sae.org/standards/content/j3400/.

Schoeck, Michael. 2023. “Subway Restaurants to Feature Battery-Buffered EV Fast Charging Stations.” *Pv Magazine USA*, February 21, 2023. https://pv-magazine-usa.com/2023/02/21/subway-restaurants-to-feature-battery-buffered-ev-fast-charging-stations/.

Schulz, Bailey. 2023. “How Reliable Are Public EV Charging Stations? Report Shows Many EV Drivers Have Issues.” *USA TODAY*, June 14, 2023. https://www.usatoday.com/story/money/cars/2023/06/14/public-ev-chargers-jd-power-reliability-study/70279294007/.

Sierzchula, William, Sjoerd Bakker, Kees Maat, and Bert van Wee. 2014. “The Influence of Financial Incentives and Other Socio-Economic Factors on Electric Vehicle Adoption.” *Energy Policy* 68 (May):183–94. https://doi.org/10.1016/j.enpol.2014.01.043.

Singer, Mark. 2020. “Plug-In Electric Vehicle Showcases: Consumer Experience and Acceptance.” NREL/TP--5400-75707, 1659790, MainId:6612. NREL. https://doi.org/10.2172/1659790.

Smart Electric Power Alliance. 2021. “The State of Managed Charging in 2021.” Smart Electric Power Alliance (SEPA). https://sepapower.org/resource/the-state-of-managed-charging-in-2021/.

———. 2023. “The State of Bidirectional Charging in 2023.” SEPA. 2023. https://sepapower.org/resource/the-state-of-bidirectional-charging-in-2023/.

Smith, Margaret, and Jonathan Castellano. 2015. “Costs Associated With Non-Residential Electric Vehicle Supply Equipment.” https://afdc.energy.gov/files/u/publication/evse_cost_report_2015.pdf.

Spencer, Alison, Stephanie Ross, and Alec Tyson. 2023. “How Americans View Electric Vehicles.” *Pew Research Center* (blog). July 13, 2023. https://www.pewresearch.org/short-reads/2023/07/13/how-americans-view-electric-vehicles/.

SRP. 2024. “Compare Residential Electric Price Plans.” 2024. https://www.srpnet.com/price-plans/residential-electric/compare-plans.

Swan, Ashleigh. 2022. “Emergency Text Averted Possible California Power Cuts.” *BBC News*, September 8, 2022, sec. Technology. https://www.bbc.com/news/technology-62832775.

The Associated Press-NORC Center for Public Affairs Research. 2023. “2023 AP-NORC/EPIC Energy Survey.” Energy Policy Institute at the University of Chicago. https://epic.uchicago.edu/wp-content/uploads/2023/04/EPIC-Energy-Policy-Survey-2023_Topline.pdf.

The White House. 2023a. “Building a Clean Energy Economy: A Guidebook to the Inflation Reduction Act’s Investments in Clean Energy and Climate Action.” https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf.

———. 2023b. “FACT SHEET: Biden-Harris Administration Announces New Standards and Major Progress for a Made-in-America National Network of Electric Vehicle Chargers.” The White House. February 15, 2023. https://www.whitehouse.gov/briefing-room/statements-releases/2023/02/15/fact-sheet-biden-harris-administration-announces-new-standards-and-major-progress-for-a-made-in-america-national-network-of-electric-vehicle-chargers/.

Transportation Energy Institute. 2018. “Driving Vehicle Sales – Utility, Affordability and Efficiency.” July 30, 2018. https://www.transportationenergy.org/research/reports/driving-vehicle-sales-utility-affordability.

Trout Electric. 2023. “EV Charging Station Installation in Riverside, CA.” Trout Electric. 2023. https://www.troutelectricusa.com/ev-charging-stations/.

UL Solutions. 2023a. “Electric Vehicle (EV) Charging Infrastructure Services.” UL Solutions. 2023. https://www.ul.com/services/electric-vehicle-ev-charging-infrastructure-services.

———. 2023b. “Marketing Guidelines for UL Solutions Customers With Product, Process, Facility or System Certifications : UL Marks and Labels.” UL Solutions. 2023. https://marks.ul.com/about/ul-listing-and-classification-marks/promotion-and-advertising-guidelines/specific-guidelines-and-rules/.

———. 2023c. “Search for Electric Vehicle Supply Equipment on Product iQ.” UL Product iQ. 2023. https://productiq.ulprospector.com/en/search?term=electric+vehicle+supply+equipment.

Uptime Charger. 2023. “Uptime Charger.” Uptime Charger. 2023. https://www.uptimecharger.com.

U.S. Department of Transportation. 2023. “EV Infrastructure Funding and Financing for Rural Areas.” May 4, 2023. https://www.transportation.gov/rural/ev/toolkit/ev-infrastructure-funding-and-financing.

———. 2024a. “Implementation Challenges and Evolving Solutions for Rural Communities.” 2024. https://www.transportation.gov/rural/ev/toolkit/ev-benefits-and-challenges/challenges-and-evolving-solutions.

———. 2024b. “Rural Eligibility.” U.S. Department of Transportation. 2024. https://www.transportation.gov/rural/eligibility.

———. 2024c. “Rural EV Infrastructure Funding Table.” April 29, 2024. https://www.transportation.gov/rural/ev/toolkit/ev-infrastructure-funding-and-financing/funding-matrix.

U.S. Utility Rate Database. 2023a. “Salt River Project E-23 BASIC PRICE PLAN FOR RESIDENTIAL SERVICE.” OpenEI. 2023. https://apps.openei.org/USURDB/rate/view/6549645e52e4d31bea0f4e7a#1__Basic_Information.

———. 2023b. “Salt River Project E-26 STANDARD PRICE PLAN FOR RESIDENTIAL TIME-OF-USE SERVICE.” OpenEI. 2023. https://apps.openei.org/USURDB/rate/view/6549645e52e4d31bea0f4e7a#1__Basic_Information.

———. 2023c. “Salt River Project E-29 Residential Electric Vehicle Price Plan.” OpenEI. 2023. https://apps.openei.org/USURDB/rate/view/6549645e52e4d31bea0f4e7a#1__Basic_Information.

White, Lee V., Andre L. Carrel, Wei Shi, and Nicole D. Sintov. 2022. “Why Are Charging Stations Associated with Electric Vehicle Adoption? Untangling Effects in Three United States Metropolitan Areas.” *Energy Research & Social Science* 89 (July):102663. https://doi.org/10.1016/j.erss.2022.102663.

Wood, Eric, Brennan Borlaug, Matthew Moniot, Dong-Yeon Lee, Yanbo Ge, Fan Yang, and Zhaocai Liu. 2023. “The 2030 National Charging Network: Estimating U.S. Light-Duty Demand for Electric Vehicle Charging Infrastructure.”

Zamanov, Nick. 2023. “Charging Station Maintenance: Key Aspects for Safe and Reliable Operation.” *Cyberswitching* (blog). April 18, 2023. https://cyberswitching.com/charging-station-maintenance/.