2023 White Paper

EVs2Scale2030™ Electric Vehicle Charging Reliability Analysis

Insights to Improving the Public Electric Vehicle Charging Experience

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Refueling conventional, gasoline-powered vehicles is a largely familiar and seamless process to the average driver. This robust system of refueling infrastructure sets a standard for Electric Vehicle (EV) charging to emulate – one of consistency, convenience, and dependability. Despite this, recent studies and consumer reports suggest that the current electric vehicle charging ecosystem fails to meet these expectations, partly attributed to the (lack of) reliability of existing public EV charging infrastructure. This issue has been seen as a challenge for EV adoption for years,[1] and has been especially highlighted by the surprising recent choice by Ford, General Motors, Rivian, Volvo, and Mercedes-Benz to adopt Tesla's charging connector. Tesla had previously stood alone as the only automaker in North America not using the Combined Charging System (CCS) standard (except for some continued use of the CHAdeMO system by Nissan and Mitsubishi), which meant that they were competing against the combined investments of other automakers, electric vehicle service providers, utilities, and various governments. However, Tesla's ability to achieve high reliability and broad coverage as a closed ecosystem has meant that Tesla drivers have a more reliable, seamless, and predictable charging experience than drivers of other vehicles.[2] As more automakers and charging suppliers try to use Tesla's connector, it is unclear whether or not the high reliability that Tesla achieved in their proprietary charging network will be maintained or will fall. The results of this work indicate that high reliability is achievable – but it will take considerable effort.

This paper is the conclusion of a 6-month effort performed as part of EPRI's EVs2Scale2030™ initiative – as the current lack of reliability of public EV charging is recognized as a critical barrier to widespread EV adoption.[3] This effort intended to identify the reasons for reliability challenges and suggest opportunities for improvement, both through analysis of data and through stakeholder interviews. However, the team quickly found that there is little quantitative data publicly available to us at this time. This means that the results are generally qualitative, but we believe there are still valuable takeaways.

The interviews revealed that there is no single point of failure that is causing reliability problems. Faults arise from a variety of sources, including components such as power converter failures, damage and vandalism, payment and network errors, and others. Resolution of faults can differ dramatically between different charge system operators due to supply chain difficulties, the availability of replacement parts, and the ability of reporting and diagnostics to quickly identify the correct problem. This leads to the main findings from the analysis: ***achieving high reliability is possible, but requires a high degree of organizational alignment and sufficient funding***. The interviews also lead to a variety of recommendations, discussed in detail below:

- Planners should assume funds are needed for operations, maintenance, and repair, not just charger installation

1 https://pluginamerica.org/survey/2023-ev-driver-survey/
2 https://www.roadandtrack.com/news/a43979303/sorry-state-of-ev-charging/
3 https://msites.epri.com/evs2scale2030

- Funding should be provided for replacing obsolete and underperforming chargers[4]
- Equipment installers should give preference to equipment that is modular and has advanced remote diagnosis functions
- Error codes should be standardized between equipment vendors
- Chargers should be physically inspected periodically, even by untrained personnel, and remotely monitored by automated systems continuously
- There should be consequences to not meeting reliability standards

INTRODUCTION

This paper is part of EPRI's EVs2Scale2030™ initiative, which aims to determine the steps necessary to achieve widespread transportation electrification by 2030. Charging reliability was identified as a challenge early in the creation of this initiative – if drivers are not able to charge reliably, they will be hesitant to use their EVs and will not recommend them to others. This has already been identified as a challenge to widespread EV adoption and a source of dissatisfaction among EV drivers.[5] However, these struggles are not universal – studies which survey charging reliability generally split into two subsets, "Tesla" and "everyone else." It is natural to associate this with the charging connector – Tesla uses their own charging standard and achieves high reliability while others use the CCS standard and generally suffer from lower reliability. However, our interviews identified areas where high charging reliability has been achieved with CCS. In fact, charging in Europe is generally considered to have relatively high reliability despite all car companies including Tesla using the CCS standard.[6] This important point is often missed in the U.S. This encouraged the team to work to identify other reasons for these reliability gaps.

A first step in analyzing reliability is determining how to measure reliability. A useful benchmark is the uptime requirement for the National Electric Vehicle Infrastructure (NEVI) Formula Program, which allocates $5 billion of funding to create a network of DC fast chargers in high-traffic corridors across the U.S. This funding program includes a provision for charger reliability, establishing a goal of 97% uptime for chargers participating in the program. This "uptime" is calculated as the percentage of time a charger's hardware and software present themselves as online and available to charge at more than 150 kW. Although achieving this consistently would be significant progress relative to current performance, there are still significant opportunities for improvement beyond this standard:

- Although the 97% uptime target is high, this still allows at least 11 days per year when the charger is not available for use. Utility electrical service, in general, has an uptime of over 99%, including the effects of extreme weather events,[7] and critical equipment similar to charging stations such as gas stations, Automated Teller Machines (ATMs), and others are considered to have much higher reliability (although the team could not find precise metrics).
- There are a variety of exceptions to the uptime calculation that may make chargers unavailable to users, but which do not count as downtime, including "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."[8] Although these factors are often outside of the charging station operator's control, they result in loss of service and should be monitored to ensure that these outages are not excessive and are mitigated to the extent possible.
- In terms of user experience, the per-charger metric may be less important than other potential metrics. For example, Tesla measures reliability based on availability of the entire station, requiring at least 50% of chargers

4 The technically correct term for external charging systems that plug into a vehicle is "Electric Vehicle Supply Equipment" since these contain numerous parts which are not part of the "charger" or do not contain a charger at all (which is actually on the vehicle). However, this report will use the more colloquial term "charger" to refer to the external equipment that is required to supply electricity to a vehicle.

5 https://www.theatlantic.com/science/archive/2023/05/where-are-the-ev-charging-stations/674241/ https://www.jdpower.com/business/press-releases/2023-us-electric-vehicle-consideration-evc-study

6 The European connector for CCS (CCS2) is physically different from the CCS1 connector used in North America, but these connectors are generally similar and the electrical signaling is identical, so this does not seem to be the primary factor in reliability differences (see https://insideevs.com/news/488143/ccs-combo-charging-standard-map-ccs1-ccs2/ for more information)

7 https://www.nerc.com/pa/RAPA/PA/Performance%20Analysis%20DL/NERC_SOR_2022.pdf

8 https://www.federalregister.gov/d/2023-03500/p-439

at a station to be functional for the entire year. This is in some ways less stringent but would allow a user to charge even if they had to wait for an available charger. Tesla also meets this standard at a higher level, consistently exceeding 99.9% availability on this metric.[9]

- The specific exclusion of vandalism in uptime calculations is important since the interviews revealed this to be a consistent source of frustration among parties operating charging networks. Given that chargers are usually unattended, are usually open at all hours, and at this time are frequently unused for many hours at time, there are ample opportunities for vandalism to occur and little that can be done to prevent it.

The team was unable to find a quantitative metric better than the NEVI requirement given the current state of the market. Our interviews indicated that a better goal to work towards would be something like the motto of the ChargeX Consortium of "first time, every time" – that a driver should be able to arrive at a charger and begin charging immediately using their preferred method of payment.[10] Although it is difficult to measure a driver's experience, this is ultimately the most important outcome.

COMMONLY IDENTIFIED POINTS OF FAILURE

A first step in improving reliability is understanding what problems are common now. Data on this is hard to acquire since there are a mix of technical and qualitative factors which may prevent a successful charging session from happening. In the interviews, five main categories recurred: components such as power converter problems, damaged or vandalized chargers, vehicle-specific incompatibilities, payment system and connectivity problems, and user error:

- **Power converter problems:** Failures of electrical components for lower power alternating current chargers appear to be relatively rare, but direct current fast chargers are complex and contain power converters that appear to be a significant source of failures. These failures can either be total, where the charger is unable to dispense power at all, or partial, where the charger still supplies some power, but less than should be expected. If the charger is not designed to enable diagnosis and repair, it may be difficult to determine the actual source of the problem and restore full operation. Notably, the NEVI requirements consider a charger to be "operational" only when it can supply at least 150 kW of power. A charger that continues to operate at a lower power level with an inoperable power converter may not meet this requirement.
- **Damaged or vandalized chargers:** In talking with parties who operate chargers, a frequent source of concern was damage or vandalism to chargers, such as cut cables, plugs damaged due to being dropped, graffiti, intentionally scratched displays, and damage from environmental factors such as sun damage. These problems are particularly problematic since they are difficult to diagnose without physical access; current chargers rarely have sensors capable of detecting this type of problem.
- **Vehicle-specific incompatibilities:** These problems occur between specific vehicle and charger combinations due to differences in the physical or electrical implementation of charging standards. Although standards generally enable compatibility, the standards for charging interfaces were sometimes imprecisely specified early in the implementation process or were incorrectly implemented by one party or the other. An example is the advice that charger help lines sometimes provide to "try connecting again, but this time push up on the bottom of the handle." In this case, plugs and sockets are different enough that a reliable connection cannot be established. This can occur due to wear or due to devices that are different enough that the weight of the cable distorts the interface. Pushing up on the handle closes the gap between electrical contacts so communication can occur. Similarly, the timing specifications of communications signals are often very precise, so slight differences in implementation (e.g., longer vehicle wiring harnesses on board the vehicle) can cause timeouts and garbled signals. There is an increased focus on testing different chargers and vehicles through "Testivals."[11] Standards have been tightened over time to prevent these problems, but legacy vehicles which are no longer being updated will cause problems in the future. It will be impossible to test every vehicle/charger combination as both markets have more options available. An additional vehicle-specific incompatibility which will be a continuing concern is cable length. There is no standard for the location of a charging port

9 https://www.tesla.com/ns_videos/2022-tesla-impact-report.pdf
10 https://inl.gov/chargex/
11 https://www.charin.global/events/global-testivals/

on the vehicle or for a charger relative to a parking space, which means that plugging a charging cable into a vehicle may require a very specific and potentially illegal parking arrangement or may be impossible. Newer chargers tend to have longer cables, but it is unclear how long they need to be and there are still no efforts to address this through standards.

- **Payment system and connectivity problems:** One common source of reported problems was the payment system. For example, in Cool the Earth's test of charging reliability only around half of successful charges could be initiated through one swipe of one credit card.[12] One of the reasons for this is that integration of credit card reading directly into a device requires compliance with the strict Payment Card Industry (PCI) standard,[13] so most chargers use a self-contained credit card reader similar to those in vending machines and simple payment kiosks. Although these can be successfully integrated, the isolation of payment information can lead to complex interactions since vehicle charging is not a common use case. As an example of this type of interaction, if a user inserts her credit card at the beginning of a charging attempt, then takes an extended amount of time plugging in her car, the credit card reader can time out and end the transaction. The charger could then be unable to reinitiate the transaction since it does not know the credit card number. Separate payment systems keep this information private. The user also may be unable to initiate a new transaction with the same credit card since the card reader back office believes there is already a duplicate transaction in process. This type of problem is the likely reason that many chargers ask the user to plug the connector into the vehicle before initiating the credit card transaction. In addition to problems with complex interactions, separate credit card readers also often require a dedicated network connection, which means that both the charger and credit card reader have the potential for network disruptions.
- **User error:** In discussing reasons for perceived reliability problems with various stakeholders, user error was raised as an important issue – the charger was working as intended, but the user did not understand the procedure for using the charger. Although user error is likely to be a significant obstacle, the aforementioned difficulties with payment systems and the unnecessary complexities of some chargers likely contribute to this problem. For example, chargers with two ports will often require a user to select which port they intend to use at the beginning of the charging procedure. A user who does not understand the differences between CHAdeMO and CCS – or that other standards even exist – will likely have difficulty making the correct selection. Many of these problems can be resolved through better user interface design.

BROAD FINDINGS FROM INTERVIEWS

The study team interviewed a variety of stakeholders in both the U.S. and Europe with different perspectives. There were some variations in responses, but some common themes emerged, as discussed in this section.

Achieving high reliability requires organizational alignment

Although it was rarely mentioned explicitly, it became clear that organizations that deliver high reliability are aligned around delivering a good charging experience. This is somewhat of a truism, but it became apparent that there were some organizations where some employees were not accountable for this experience or were not enabled to make the necessary changes to achieve it. An example of this was in difficulties around subcontracting. Charging is an emerging business with numerous complexities, meaning few companies can control the full process of installing, operating, and repairing chargers, so subcontractors were required. However, we heard many instances of poor performance from subcontractors and an inability of lower-level employees to modify these contracts or improve performance in the future. This leads to finger pointing and frustration but does not lead to high reliability.

Organizations that achieved high reliability appeared to use multiple methods to assess performance and work toward the resolution of problems. For example, in addition to software dashboards enabled by the networking built into the charger, some organizations would track call center calls, monitor social media, look through logs for anomalous charging events, or periodically physically inspect chargers.

12 Cullen, David Rempel, Mary Matteson Bryan, and Gustavo Vianna Cezar. "Reliability of Open Public Electric Vehicle Direct Current Fast Chargers." arXiv preprint arXiv:2203.16372 (2022).

13 https://www.pcisecuritystandards.org/

Once problems were identified, the top performing organizations initiated a rapid response process to assess problems and fix them immediately if possible.

Achieving high reliability is going to be more expensive than many estimate

One reason for these organizational difficulties is that achieving high reliability appears quite expensive, at least in the near term. This is because recognizing many faults requires vigilance and physical inspections, and quickly repairing faults requires the availability of critical components and training and retention of qualified personnel. For example, in their fast charging design and operations guide, BC Hydro – who was recognized numerous times as a leader in charging reliability – recommends weekly inspections, warehousing of critical parts such as connector cables, and the ability to obtain all parts within 24 hours.[14] We heard from various parties that ideally the necessary parts would be on the truck that goes to diagnose the problem so only one "truck roll" would be required to restore full operation. However, this requires advanced remote diagnosis and is difficult when supporting a variety of charger types.

The warehousing of components described above can be a considerable expense. Although it is difficult to obtain precise estimates for this, one charging system operator estimated the cost of inventory at one-third to one-half the cost of each charger. Many parties were able to achieve this for "level 2" chargers, which generally cost around $2k each, but direct current fast chargers cost $50k or more, so this is a relatively high cost for spare parts. However, a charger can be rendered inoperable by something as simple as a damaged charging cable or interface screen. Some level of cost-optimized parts management may be sufficient to significantly increase reliability.

In addition to having spare parts to repair broken chargers, it was apparent that sometimes full replacement was required. This is especially true of some chargers that were early to the market and had less testing than current designs but was also reported to be true of some newer chargers. There were numerous reports of "problem" chargers that had repeated problems, even if an identical charger next to them did not. Replacing entire chargers can be expensive, but it appears to be necessary to prevent recurring problems.

Achieving high reliability is possible

A more positive note that emerged from the interviews is that there was widespread agreement that high reliability is possible if sufficient resources are deployed.

RECOMMENDATIONS

The interviews conducted for this paper and the process of trying to align the different viewpoints expressed have led to a number of broad recommendations, discussed in this section.

Planners should assume funds are needed for operations, maintenance, and repair, not just charger installation

Grant programs or private funding should be allocated with the understanding that operations, maintenance, and repair will be a significant share of the overall costs. The study team does not have a specific recommendation for this. Funders without experience with these costs may allocate funding flexibly to allow reallocation as experience emerges. Funding agreements should require recipients to provide visibility into actual costs.

This seems obvious and is written into NEVI guidance, which recommends funding 5 years of operations and maintenance expenses. However, installing chargers seems to be more appealing than fixing them. The study team is aware of at least one state that forbids their NEVI funding from being spent on these expenses to maximize the number of chargers installed (NEVI sets guidelines, but states make their own decisions about the precise terms of their programs).

Funding should be provided for replacing obsolete and underperforming chargers

Given numerous gaps in the current charging network it seems prudent to focus on expanding the network rather than replacing equipment that works some of the time and was likely installed only a few years ago. However, it

14 https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/power-smart/electric-vehicles/BCHydro-EV-Fast-Charging-Guidelines.pdf

appears that there are some "lemon" chargers just as there are lemon cars, and that replacing this equipment entirely is the only way to achieve high reliability. Much of this can be achieved through well-written warrantee agreements. However, multiple parties disclosed that their warrantee did not cover this type of problem or that their supplier went out of business and was unable to honor it.

Equipment installers should give preference to equipment that is modular and has advanced remote diagnosis functions

One interesting recommendation that came from numerous parties is to investigate newer generations of equipment that are highly modular and are designed for operation despite partial failures. As an example, some charging systems have cabinets with multiple small power converters that are capable of supplying multiple charging ports. Supplying maximum power to a given port requires a collection of converters, for example 6-8 converters all allocated to one port, but even a failure of one converter still allows operation at close to full power. Additionally, if these converters are overprovisioned to start with, it is possible that there will be no service interruption at all. This also decreases the inventory of parts required and speeds repair, since instead of having to diagnose and repair the individual components of a converter, the entire converter can be swapped for later reconditioning. NEVI guidance anticipates this type of charger by allowing chargers that are designed to operate at high power levels (for example, 350 kW) to count as "operational" as long as they are able to dispense at least 150 kW.

Before chargers can be repaired, though, problems have to be identified. Currently there is little standardization in remote diagnostic functions, but quickly detecting failures and identifying the component responsible for the failure will enable more rapid resolution and can potentially allow a problem to be solved with one truck roll. At least one charger manufacturer is also installing cameras and microphones on the charger itself, allowing communication with customers that are experiencing a problem and potentially allowing a larger variety of problems to be detected.[15]

15 https://www.motortrend.com/news/flo-ev-electric-charging-station-reliability/

Error codes should be standardized between equipment vendors

One source of frustration we heard from parties which operated fleets of varied chargers was the lack of standardization of error messages. Although chargers are generally required to report problems through Open Charge Point Protocol, this protocol has a limited set of error messages and generally debugging any significant problem requires decoding proprietary error codes. These vary between charger vendors and can even vary between versions, meaning that fault diagnosis is very labor intensive. The study team is aware of ongoing efforts to work towards this standardization, including through the ChargeX Consortium, and hopes this effort is successful and quickly adopted.

In addition to the standardization of error codes, it would be useful to create messages for anomalies which are not necessarily errors but are unexpected. Examples of this are charging sessions that are very short, apparent attempts to use the plug that result in no charging, and cases of one charger being used immediately after an attempt was made with an adjacent charger. Some of the charging operators we interviewed reported manually combing through logs to find problems like this, but it is so labor intensive that it was usually only done after a known problem occurred. Chargers could also incorporate additional sensors to understand their immediate environment, such as vibration, excessive temperature, the presence of water, or whether or not a car is parked in the spot they serve. The study team was informed that ATMs incorporate around 200 sensors to detect problems throughout the machine and its surroundings.

Chargers should be physically inspected periodically, even by untrained personnel, and remotely monitored by automated systems continuously

There are many challenges which are difficult to diagnose remotely, such as broken connectors, vandalism, and parking blocked by vehicles or snow. Physically visiting chargers allows these problems to be identified and ensures that chargers that are otherwise operational are actually available to charging customers. Although some charging systems operators have employees drive around and visit the chargers, charging plazas are now being installed at facilities with existing personnel, such as Circle K and Walmart.[16] Even if the on-site personnel are not trained on fault diagnosis and repair, just being able to see problems in person and communicate with EV drivers will have value. In many cases, they will be able to take appropriate actions to have the problems fixed. In addition to periodic physical inspections, remote monitoring can be automated to allow continuous detection of potential problems. This is already being done to some degree, especially through vendor-specific portals, but the study team communicated with a number of parties that see improving this as an emerging business opportunity.

There should be consequences to not meeting reliability standards

As described above, the NEVI guidance has well-defined requirements for uptime. However, the guidance does not contain consequences for failing to meet these requirements such as funding clawbacks or restricted ability to bid on future funding rounds. The NEVI team has stated that states are able to set their own enforcement mechanism, like they do with contracts for other goods and services, but the study team was not able to identify any states that have done so (the study team is aware of two states that had clawback previsions in initial versions of their funding requirements, but these were left out of the final versions). The NEVI guidance does require data on availability and usage to be publicly available to all parties, so there will likely be “name and shame” consequences for operators that do a poor job of meeting the requirements. However, it is unclear if this will provide sufficient incentive for good performance.

16 https://corporate.walmart.com/newsroom/2023/04/06/leading-the-charge-walmart-announces-plan-to-expand-electric-vehicle-charging-network

https://www.circlek.com/charge

Many parties raised an idea that would provide a partial consequence for poor performance: “fail to free.” In this case, chargers with inoperable payment systems or network connection would allow drivers to charge for free, for example providing 20 kWh to allow drivers to reach the next charger in the charging networks (as described above, payment system problems were a common source of charging failures). NEVI guidance does require chargers to supply power if they are able in the case of a loss of network connectivity, but it is unclear how this will be enforced in practice. As we work towards widespread transportation electrification, demonstrating a highly reliable and fast charging EV experience for consumers and fleet operators over the next 5 years seems critically important and this particular recommendation may be needed to guarantee a positive EV driver experience.

LOOKING FORWARD

This study is intended as a starting point for investigating charging reliability as part of EPRI’s EVs2Scale2030™ initiative, but work will continue. As part of this initiative EPRI will continue to work to get better reliability data and will be a collaborator in the national ChargeX Consortium. The study team welcomes information and feedback to help improve reliability to the point where drivers think about it as they think about reliability of gas pumps and ATMs – they do not think about it at all.

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

Export Control Restrictions

Access to and use of this EPRI product is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or U.S. permanent resident is permitted access under applicable U.S. and foreign export laws and regulations.

In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI product, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case by case basis an informal assessment of the applicable U.S. export classification for specific EPRI products, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes.

Your obligations regarding U.S. export control requirements apply during and after you and your company's engagement with EPRI. To be clear, the obligations continue after your retirement or other departure from your company, and include any knowledge retained after gaining access to EPRI products.

You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of this EPRI product hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

EPRI CONTACT

MARCUS ALEXANDER, *Technical Leader III*
650.855.2489, malexand@epri.com

For more information, contact:

EPRI Customer Assistance Center
800.313.3774 • askepri@epri.com

3002028055

August 2023

EPRI

3420 Hillview Avenue, Palo Alto, California 94304-1338 USA • 650.855.2121 • www.epri.com