2023

Fiscal Year in Review

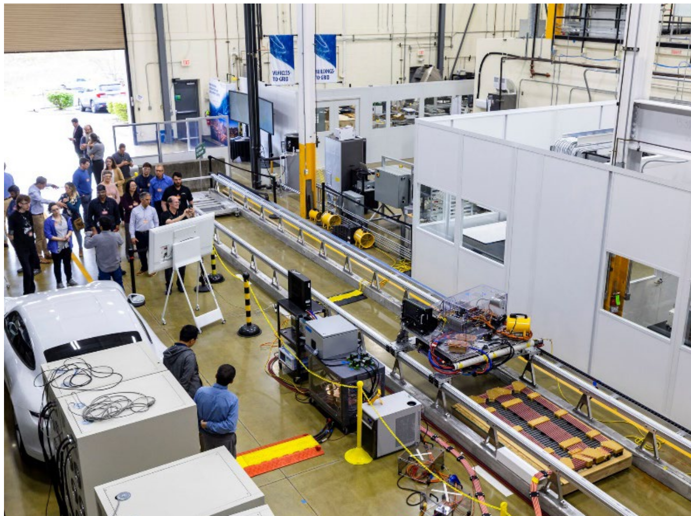
Electric Vehicles at Scale Laboratory Consortium

EVs@Scale
U.S. Department of Energy

U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Disclaimer

Photos (left to right): INL, NREL, ORNL



About the Consortium

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Photo: INL

ABOUT THE ELECTRIC VEHICLES AT SCALE (EVS@SCALE) LABORATORY CONSORTIUM

The U.S. Department of Energy's (DOE's) Electric Vehicles at Scale (EVs@Scale) Laboratory Consortium brings together seven national laboratories—Argonne National Laboratory (ANL), Idaho National Laboratory (INL), Lawrence Berkeley National Laboratory (LBNL), National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL), and Sandia National Laboratories (SNL)—and key stakeholders to conduct electric vehicle (EV) charging and grid infrastructure research and development. R&D will address challenges and barriers to high-power EV charging at scale that enables increased safety, grid operation reliability, and consumer confidence. This will also move the nation closer to a net-zero-emissions future. EVs@Scale research advances innovations in and supports standards development for on-road and off-road vehicle charging. R&D also includes technologies to integrate vehicle charging with the electric grid and develop cybersecurity measures to protect drivers, vehicles, equipment, and the grid from multifaceted threats.

The advanced technologies developed by the consortium will help make charging an EV as safe, convenient, and seamless as fueling a gas-powered vehicle, as well as make it easy to find an EV charging station. This will motivate increased consumer adoption and benefit all communities, including those in underserved urban and rural areas. The consortium will also identify and develop technologies to charge the large batteries required for freight trucks and buses efficiently, affordably, and securely, to ultimately reduce transportation emissions. The smart charging strategies, technologies, and support to standards development by the consortium will help electrify air, marine, rail, and other off-road transportation modes.

Ensuring that the grid infrastructure remains reliable by defending against cyberthreats is crucial to supporting EV charging needs. Internet-connected systems help control everything from balancing the grid's electricity supply to processing charging station payments. The consortium's work to avert any possible attacks on the electric grid or a charging network will protect vehicle and electrical systems and increase consumer confidence in EVs. This consortium addresses key R&D opportunities:

- Develop grid planning strategies and vehicle control methods, also known as **vehicle-grid integration (VGI) and smart charge management (SCM)**, to mitigate grid disruptions caused by the increase in higher-power electric vehicle supply equipment (EVSE).
- Expand **high-power charging** opportunities, including improving long-term efficiencies and reducing investment and operation costs. Efforts target increasing charging equipment power densities to address the lack of high-voltage, high-current devices for power electronics, interconnection requirements necessary for multimegawatt charging sites, and modularity across sites to support the correct balance and commonality.
- Address the evolving threats and challenges to the EV charging ecosystem through **cyber-physical security** research and validation of the most feasible solutions to ensure safe, secure, and resilient charging operation. The security of EV charging infrastructure is critical to protect EV users, the EV charging network, and the grid.
- Harmonize **codes and standards** by identifying and addressing challenges and barriers created by conflicting standards and requirements to help integrate at-scale EV charging with the grid. Technical standards are imperative to the development, deployment, and adoption of advanced EV charging and grid integration technologies; uncoordinated development of codes and standards will create inconsistencies that will impede the deployment of secure and scalable charging systems.

Although 2023 saw the nation still recovering from supply chain issues, our consortium members continued cross-laboratory research and collaboration with the same rigor as the year prior. As a testament to this, we successfully hosted our second and third Semiannual Stakeholder Meeting in person at ORNL and ANL, respectively.

Photo: iStock

Photo: NREL

We convened virtually with our stakeholder advisory group members and hosted a series of deep-dive technical meetings to further engage our stakeholders, with a higher attendance average per session than last year. Finally, we also welcomed LBNL and the Advanced Charging and Grid Interface Technologies research pillar to the consortium.

As Fiscal Year (FY) 2024 begins, we continue to advance EV technologies on all fronts through our R&D. We thank the leadership of the Vehicle Technologies Office (VTO) under DOE's Office of Energy Efficiency & Renewable Energy for their continued support of this consortium. We also thank our stakeholder advisory group for their continued feedback, which has had a positive impact on the achievements of this consortium in its second year.

EVS@SCALE LEADERSHIP TEAM

Andrew Meintz
National Renewable Energy Laboratory

Tim Pennington
Idaho National Laboratory

Dan Dobrzynski
Argonne National Laboratory

Bin Wang
Lawrence Berkeley National Laboratory

Donald Stanton
Oak Ridge National Laboratory

Lori Ross O'Neil
Pacific Northwest National Laboratory

Craig Lawton
Sandia National Laboratories

Partners

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NREL Transforming ENERGY

Argonne NATIONAL LABORATORY

Pacific Northwest NATIONAL LABORATORY

INL Idaho National Laboratory

BERKELEY LAB

OAK RIDGE National Laboratory

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office

Austin Brown
Director

Lee Slezak
Technology Development Manager

Fernando Salcedo
Technology Development Manager

Donald Hillebrand
Senior Advisor

Michael Weismiller
Program Manager

Rob McDonald
Senior Engineer

Fred Wagner
Senior Engineer

Richard Bogacz
Senior Energy Policy Analyst

LEADERSHIP COUNCIL

Argonne National Laboratory

Dan Dobrzynski

Idaho National Laboratory

Tim Pennington

National Renewable Energy Laboratory

Andrew Meintz

Oak Ridge National Laboratory

Donald Stanton

Pacific Northwest National Laboratory

Lori Ross O'Neil

Sandia National Laboratories

Craig Lawton

RESEARCH PILLAR LEADS

Vehicle-Grid Integration & Smart Charge Management

Jesse Bennett
National Renewable Energy Laboratory

Jason Harper
Argonne National Laboratory

High-Power Charging

John Kisacikoglu
National Renewable Energy Laboratory

Advanced Charging and Grid Interface Technologies

Madhu Chinthavali
Oak Ridge National Laboratory

Cyber-Physical Security

Richard "Barney" Carlson
Idaho National Laboratory

Craig Rodine
Sandia National Laboratories

Codes & Standards

Ted Bohn
Argonne National Laboratory

Photo: NREL

Stakeholders Help Navigate EVs@Scale Priorities

DOE's Office of Energy Efficiency and Renewable Energy and Office of Electricity are continuing to move the nation to 100% clean electricity with the VGI Initiative. The EVs@Scale team—along with many others advancing EV technologies to achieve this goal—are ambitiously advancing the electrification of the transportation sector. The consortium continued to engage stakeholders and the public during FY 2023 to refine these plans with input on priorities and needs.

The EVs@Scale Semiannual Stakeholder Meetings, hosted by ORNL and ANL this fiscal year, were two such opportunities. Stakeholders from government, academia, industry, and national laboratories convened to identify R&D opportunities to accelerate at-scale EV-grid integration and enabling technologies. During ORNL's meeting, stakeholders toured DOE's National Transportation Research Center (NTRC) and Grid Research Integration and Deployment Center (GRID-C) and ORNL's Manufacturing Demonstration Facility. In GRID-C, participants saw the latest advancements in dynamic wireless charging and VGI and learned about transportation decarbonization efforts at NTRC including carbon capture, hydrogen research, and power electronics. During ANL's meeting, stakeholders saw Argonne's Smart Energy Plaza, home to the laboratory's Interoperability Center designed to conduct research on the integration and management of EV charging, renewables, building systems, and energy storage.

The EVs@Scale Lab Consortium correspondingly continued to update its webpages with consortium publications to further engage the public, stakeholders, and potential partners. The consortium's webpages are published under the VTO website's "Batteries, Charging, and Electric Vehicles" section and include updates about upcoming events.

The consortium also reconvened industry members to form the EVs@Scale stakeholder advisory group, a tight-knit group of key stakeholders, to continue in-depth conversations about challenges and opportunities facing the consortium's research.

The stakeholder advisory group, along with the public and other attendees of the Semiannual Stakeholder Meetings, were invited to the EVs@Scale Deep-Dive Technical Meetings that covered:

- **Smart Charge Management (SCM) and Grid Integration** – Discussions on grid, vehicle charge modeling, and analysis for EVs@Scale, as well as research, development, and deployment efforts for SCM.
- **High-Power Charging** – Discussion on high-power charging profiles for next-generation EVs, state-of-the-art high-power charging equipment performance characterization, direct-current (DC) charging hub approaches, and site energy management system modeling.
- **Wireless Power Transfer** – Review of dynamic wireless power transfer system development, validation, characterization, power electronics and control system design, advanced control techniques, and use case analysis.
- **Cyber-Physical Security** – Discussion on background and applications of charge scheduling, EVrest workplace charge reservation development and demonstration, and OptiQ smart alternating-current (AC) Level 2 EVSE development and demonstration.
- **Codes and Standards** – Discussions on the American National Standards Institute's Electric Vehicles Standards Panel EV roadmap, J3271 Megawatt Charging System (MCS) EVoke on P2030.13 and energy services exchange implementation, and national lab standards support activities.

We are actively seeking partnerships to increase our impact. We bring together cutting-edge resources from DOE and our national laboratories and are well positioned to include stakeholders in our various research projects, scaling up our initiatives to educate the public about our work.

Photos: ORNL

EVs@Scale Supports DOE Vehicle-Grid Integration Initiative

The Office of Energy Efficiency and Renewable Energy and the Office of Electricity are moving the nation to 100% clean electricity, and the transportation sector is no exception. As transportation is one of the largest contributors to the nation's carbon emissions, the VGI Initiative examines the potential impacts of EV integration with the grid—especially as the EV market continues to expand—on grid reliability and resiliency to achieve a carbon-free electricity sector by 2035.

Collaboration across offices is one way in which DOE is developing affordable, efficient, and clean transportation options to tackle the climate crisis and accelerate the development of innovative transportation technologies. The VGI Initiative focuses on driving a coordinated approach across the DOE, the U.S. Department of Transportation, the U.S. Environmental Protection Agency, and the U.S. Department of Housing and Urban Development to fully decarbonize the transportation sector.

The EVs@Scale Lab Consortium is one of five core VGI initiatives; it conducts infrastructure research and development to address challenges and barriers for high-power EV charging infrastructure that enable greater safety, grid operation reliability, and consumer confidence. EVGrid Assist supports decision makers as they plan for the future of electrification with technical assistance. The Vehicle-to-Everything (V2X) memorandum of understanding evaluates technical and economic feasibility as we integrate bidirectional charging into energy infrastructure and will also advance cybersecurity as a core component of V2X charging infrastructure. Taken together with two research portfolios, the VGI Initiative is well aligned to help bring the transportation sector closer to a net-zero-emission future.

Photos: ANL

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DOE's national laboratories possess unique instruments and facilities, many of which are found nowhere else in the world. For more than 75 years, national laboratories have collaborated to further U.S. energy independence and leadership in clean technologies, promote innovation that advances U.S. economic competitiveness, and conduct research of the highest caliber. The EVs@Scale Lab Consortium is proof of this.

Research institutions, federal agencies, nonprofits, academia, and industry often establish partnerships with our laboratories to help pinpoint R&D needs, potential issues, and mitigation strategies in all areas of our research. These partnerships produce world-class research that informs the best solutions for the greatest scientific challenges of our time—without regard to organizational boundaries. The national labs and Office of Energy Efficiency & Renewable Energy recognize that continued exchanges with these partners help focus and prioritize EVs@Scale R&D on areas with the greatest chance for near-term market impact.

Will you join us?

Contact us at evsscale@googlegroups.com.

See the EVs@Scale website for more detail on the most significant EVs@Scale accomplishments and to learn more about our consortium partnerships: energy.gov/eere/vehicles/electric-vehicles-scale-consortium.

Photo: NREL

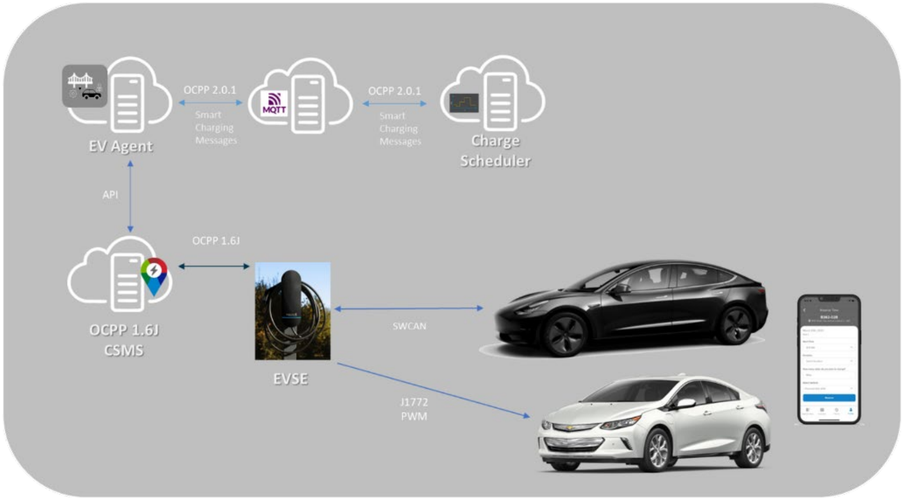
PLATFORM DEVELOPMENT TO INTELLIGENTLY SCHEDULE EV CHARGING ADDRESSES CHALLENGES

Achievement: Developed a middleware application integrated into an EV driver reservation application to integrate non-ISO-15118-enabled vehicles into the smart grid by deploying an EV agent to represent the EV driver and coordinate a charge schedule with the platform's ISO 15118 charge schedule application.

Impact: Enabling EV charge scheduling for any SAE J1772-enabled EV and Open Charge Point Protocol (OCPP) 1.6J-enabled EVSE improves the EVrest platform to conduct a demonstration of charge scheduling that will help alleviate the demand for charging on the power grid.

As the number of EVs charging on the grid increases, the need to implement intelligent and optimized charging strategies to accommodate this growing demand on the grid increases as well. "Smart," or optimized, charging considers the unique needs of all stakeholders in the EV charging ecosystem and aims to meet those needs within the limitations of the grid. One form of smart charging is charge scheduling, which can be accomplished via the ISO 15118 and OCPP 2.0.1 protocols. EVs capable of engaging in high-level digital communication with EVSE using the ISO 15118 protocol can negotiate a charge schedule with a charge scheduling application. Currently, the number of deployed ISO 15118-enabled AC EV/EVSE units is low, making it challenging to implement charge scheduling for EVs.

By leveraging ANL's EV driver reservation app, EVrest, consortium engineers have designed a platform capable of seamlessly integrating non-ISO-15118-enabled vehicles into the smart grid. This achievement is made possible through the development of a middleware application, known as the Charge Schedule Bridge, which deploys an EV agent to represent the EV driver and coordinate a charge schedule with the platform's ISO 15118 charge schedule application. The research's primary objective was to enable EV charge scheduling for any SAE J1772-enabled EV and OCPP 1.6J-enabled EVSE, and subsequently integrate this charging mechanism into the EVrest platform. Consortium research engineers will continue their work on refining the Charge Schedule Bridge, planning to incorporate it into the EVrest pilot and conduct a demonstration of charge scheduling with EVs.



Photos: ANL

The Charge Schedule Bridge is based on ANL's driver reservation application, EVrest, and integrates non-ISO-15118-enabled vehicles into the smart grid by deploying an EV agent to represent the EV driver and coordinate a charge schedule with the platform's ISO 15118 charge schedule application.

Photo: NREL

AGENT-BASED MODEL (ABM) SIMULATIONS CONSIDER INCENTIVES FOR CHARGING TO AVOID EXCESSIVE HIGH POWER ON DISTRIBUTED CHARGING

Achievement: Developed an ABM that can simulate charging behavior that represents, to the extent possible, what a human EV driver would do under different scenarios.

Impact: Simulating realistic trip chains of tens to hundreds of thousands of vehicles assesses the charging needs at different classes of chargers (private residential, semiprivate workplace, public Level 2, and public Level 3) and helps determine where to concentrate research on human charging behavior.

The consortium's SNL and INL teams collaborated to identify optimal charging locations in the Richmond and Newport News areas of Virginia. Charging station locations provided by SNL, optimized to serve users without private access, were augmented with locations picked to coincide with existing gasoline filling stations, filtered by reachability from travel routes of interest. The teams then developed ABMs that can simulate charging behavior that represents what a human EV driver would do under different scenarios. The location of public charging equipment was determined through an analysis of traffic, infrastructure, and census data, with the purpose of locating equipment to serve segments of the population who do not have access to private charging. Simulating realistic trip chains of tens to hundreds of thousands of vehicles assesses the charging needs at different classes of chargers (private residential, semiprivate workplace, public Level 2, and public Level 3). The ability to shift charging in time and location to mitigate excessive load is considered through ABMs, where agents respond to price incentives.

The ABMs consider factors such as battery state of charge and congestion. Itineraries and charging sessions are generated in one of two ways. In the first, trip origins and destinations, together with associated EVSE, are provided by NREL though the Electric Vehicle Infrastructure – Projection (EVI-Pro) tool, and the route is determined by using a route optimization technique integrated with the Caldera platform. Given a route, Caldera can either schedule charging by guiding vehicles to make optimal charging decisions, or provide information to drivers, who then apply heuristic rules to decide when and where to charge. The use of public charging infrastructure also depends on the fraction of itineraries in which cars have access to private charging. In the second method, the SNL team is developing a method to provide itineraries that reflect origin-destination pair statistics while at the same time reflecting the fact that typical itineraries also have a home location and a work location. These origin-destination pairs can then be used in the same way as the EVI-Pro ones to generate detailed itineraries and charging events. Moving forward, the SNL and INL teams will examine charging patterns that emerge from the different approaches (e.g., centrally optimized scheduling vs. heuristic ABM behavior vs. range-anxiety-driven ABM behavior) to determine sensitivities to the approach. This will be useful to determine where to concentrate research on human charging behavior. This will also inform the design of the planned workshop and surveys to inform the models, which the team expects to conduct in summer 2024.

ASSESSMENT OF NEW VGI AND SCM STRATEGIES ALLEVIATES ISSUES ON DISTRIBUTION FEEDERS AND BULK TRANSMISSION AND STRATEGICALLY SHIFTS PLUG-IN EV CHARGING TIME

> **Achievement:** Conducted an initial time-series power flow analysis integrating a real-world utility feeder model with actual EV charging data.
>
> **Impact:** By incorporating realistic time-of-use (TOU) tariff structures, the analysis helps identify the impact of such controls on the distribution feeder, and ultimately helps conduct impact analysis of EV integration with the grid.

The consortium team conducted an initial time-series power flow analysis to assess the efficacy of different SCM strategies and identify issues on the distribution feeder. Critical to this process is utilizing a newly developed co-simulation framework of integrating a real-world utility feeder model with actual EV charging data. This method allows for a comprehensive and realistic analysis of SCM methods.

The focus of this initial project milestone was to implement and assess the uncontrolled EV charging scenario, as well as some of the developed EV charging strategies, on a selected distribution network. This process facilitates the identification and understanding of challenges within the distribution network planning and operation, ultimately contributing to the development of more effective SCM strategies. The initial EV control strategies to be implemented involve TOU, representing a reasonable period (in the day) to study the impacts of TOU-based controls in shifting EV charging demand. By incorporating realistic TOU tariff structures, the analysis aims to identify the impact of such controls on the distribution feeder. This milestone marks a crucial stage in the project, representing the initiation of impact analysis of EV integration with the grid.

The milestone was accomplished with initial insights from the impacts of the implemented EV charging strategies. The time-series power flow simulation of EV charging control scenarios on the selected real-world distribution network was conducted utilizing the co-simulation framework. Two TOU-based charging strategies—TOU ASAP and TOU random start—were evaluated in the initial step, along with the uncontrolled charging scenario. A TOU tariff-based time structure adopted by the utility collaborator, Dominion Energy, was utilized. The super off-peak period was between 12 a.m. and 5 a.m. A highly residential feeder was selected to study the impact on the distribution grid. Grid impact analysis includes the comparison of uncontrolled charging, TOU ASAP charging, and TOU random start charging scenarios with the baseline scenario (representing the existing condition of the power grid without EVs).

The initial grid impact analysis results show that the uncontrolled EV charging added about 20% additional demand on the existing grid. Uncontrolled charging added more loads to the grid during evening hours, as expected. In general, most EV owners get back home during the evening hours and plug in their EV for charging. On the other hand, charging at super off-peak hours in the TOU-based scenarios created a larger peak during the midnight hours. The TOU ASAP strategy involves charging as soon as the super off-peak duration starts, leading to a huge rise in power draw and highly overloaded service transformers.

Conversely, the TOU random start charging strategy allows charging to start randomly within certain hours of the beginning of the super off-peak period. This distributed the charging within the first few hours, relieving the grid from a sudden rise in demand. However, the super off-peak hours considered were not enough to minimize the demand. This analysis shows that the existing TOU rate structures could magnify the grid impacts of EV charging. These grid impacts would be the result of the flexibility of EV charging and the potential for timer peaks if drivers schedule charging to only occur during favorable pricing windows. However, simple modifications to the TOU-based controls, specifically randomization of the charge session start within the vehicle dwell and TOU periods, could minimize the impacts on the grid while ensuring drivers still satisfy all their energy needs. Overall, the analysis showed that the TOU-based charging strategies considered create a potential risk for greater impacts with TOU charge scheduling peaks but could also be easily mitigated and improve upon the uncontrolled scenarios through simple modifications such as those in the TOU random control.

Moving forward, some assumptions in the analysis will be updated. For example, the load profiles considered can be replaced with load profiles that more accurately represent the feeders. Other components will be added, such as a new TOU-based window and analysis for a wider region that incorporates a higher number of feeders and more control strategies. Additionally, the team will develop metrics and methodologies to present the outcomes.

PROOF-OF-CONCEPT DC CHARGING HUB PLATFORM AND ENABLING TECHNOLOGIES PREPARE FOR PILOTS

Achievement: Created an experimental interoperable, DC-coupled charging hardware platform that is open to innovation for different controller algorithms to be implemented within the hub and published technical report documenting progress.

Impact: Addresses a need and provides a guideline for designing and validating efficient, low-cost, reliable, and interoperable hardware for DC-hub-based charging, communication, and control architecture.

The High-Power Electric Vehicle Charging Hub Integration Platform (eCHIP) project aims to develop hardware and software solutions for a DC distribution-based charging hub platform. To develop and demonstrate various integration approaches and technology solutions for the DC hub, the consortium team created an experimental interoperable charging platform that is open to innovation for different controller algorithms within the hub. The DC hub platform integrates EVs, battery energy storage system, photovoltaic system, and building loads to demonstrate the flexibility of the platform. A grid-tied inverter rated at 660 kW established a 950-V DC bus, from which all loads received power. An open-source site energy management system controlled the devices within the hub using a rule-based implementation and realized available standards. Bidirectional power transfer was furthermore achieved using ISO 15118-2 by ANL, which successfully discharged an electric bus. A controller hardware-in-the-loop system was also developed to simulate large-scale hub operations in real time.

This platform addresses a need to design and validate efficient, low-cost, reliable, and interoperable hardware for DC-hub-based charging, communication, and control architecture. The charging hardware platform and open-source site energy management system enable development and testing of innovative controllers and new DC/DC chargers. Moving forward, the project will focus on demonstrating real-world use cases, including the development and implementation of optimized and distributed controllers with the hardware platform. An in-house DC/DC charger developed by ORNL will additionally be integrated.

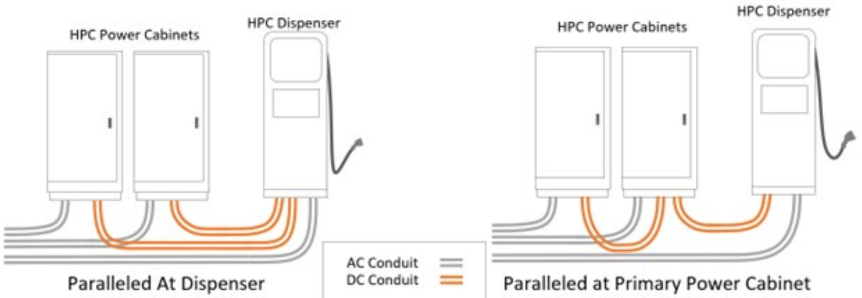
The consortium team also produced a report that details the design and development process of the high-power, interoperable charging test bed progressed under eCHIP. It is the project team's first comprehensive deliverable document that summarizes the progress made toward the development and specifications of the DC charging hub, including integration approaches and technology solutions available in the industry and the literature, with special consideration for perspectives on practicality and implementation. The report also explains the project approach, providing guidelines on important metrics and considerations. Ultimately, the report is a living document that will improve.

The eCHIP project setup at NREL

The eCHIP project setup at ANL

Photos (top to bottom): NREL, ANL

The NextGen Profiles team conducts a cold soak test when EV and EVSE charging characteristics are assessed when it meets the team's specific cold-temperature conditions.



Photos (top to bottom): NREL, ANL

The NextGen Profiles project tests characterized DC charging stations with two differing topologies for high-power charging EVSE systems: a paralleled system that is coupled at the dispenser, and a paralleled system that is coupled at the primary cabinet.

NEXT-GENERATION PROFILES (NEXTGEN PROFILES) PROJECT ANALYSES AND REPORTS HELP IMPROVE HIGH-POWER CHARGING SYSTEMS AND VEHICLES

Achievement: A technical report series was published to make the details of charging test results collected from 19 EVs and 7 EV charging systems, as well as analyses of 5 electrified public transit fleet usage patterns, broadly available.

Impact: The reports provide valuable objective performance data for industry stakeholders to improve current EVs and infrastructure and educate and inform the public about existing costs and barriers associated with electrifying transportation.

Conducting characterization tests can improve control performance of high-power charging systems and vehicles that experience abnormal conditions such as grid voltage, frequency, and temperature fluctuations. The consortium's NextGen Profiles project assesses EVs and EVSE that are expected to utilize high-power charging. The research aims to understand how high-power charging systems respond to grid disturbances and SCM scenarios, as well as analyze how electric fleets perform. Original equipment manufacturers, industry stakeholders, and EV suppliers partner with the consortium team to validate EV assets and refine validation procedures. Ultimately, the project seeks to develop a knowledge base that will inform high-power charging infrastructure planning, integration of storage and renewables, and ensure that the transition to EVs is reliable.

To achieve these goals, the consortium's NextGen Profiles project team authored four technical reports. The report series details charging test results collected from 19 EVs and 7 EV charging systems, as well as analyses of 5 electrified public transit fleet usage patterns. The reports provide valuable objective performance data for industry stakeholders to improve current EVs and infrastructure. Results shared in the reports also educate and inform the public about existing costs and barriers associated with electrifying transportation.

In the second quarter of FY 2024, the project team will review and revise test procedures to accommodate an expansion of the NextGen Profiles project scope, optimize test and invested resource value, and continue cold weather EV profile capture and EVSE characterization data collection.

DEVELOPMENT OF CYBERSECURITY RESPONSE & RECOVERY METHODOLOGIES FOR HIGH-POWER DC CHARGING INFRASTRUCTURE

Achievement: A cybersecurity mitigation solution named Cerberus was developed for high-power DC charging infrastructure to detect, respond to, and recover from a wide range of cyber exploits and anomalous events.

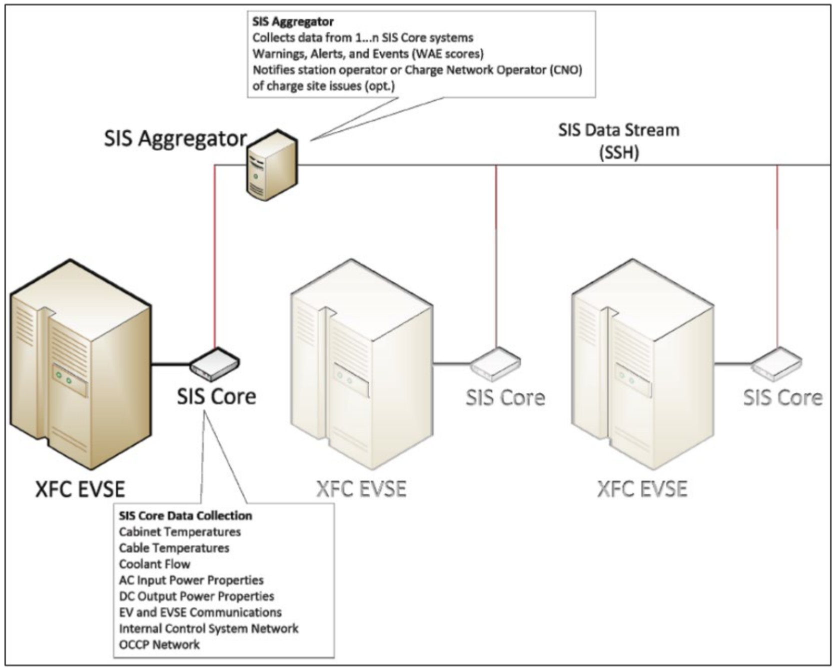
Impact: This mitigation solution not only ensures continued resilient functionality, but also greatly reduces potential safety risks, negative grid impacts, and hardware damage to the charging infrastructure.

The mitigation solution named Cerberus was styled after an industrial safety instrumented system (SIS) that is typically used for large automated industrial systems where safety and resiliency are critical. The Cerberus system incorporates similar features as an SIS, including monitoring all internal and external communications as well as physical measurement of critical systems properties to ensure safe and resilient operation.

The Cerberus system comprises two types of modules. A "core" module is integrated into each charger (EVSE) at a charge station site and a single "aggregator" module is integrated into the charge site to coordinate the numerous core modules. Each core module can detect and prioritize anomalous event into categories: "Warnings," "Alerts," or "Errors." From this information, the core module or the aggregator module can respond appropriately to prevent or minimize the impact severity of the event. Additionally, the Cerberus system can execute recovery action to ensure continued resilient charging functionality.

Cerberus fills a gap in mitigation solutions and best practices for high-power DC charging infrastructure. Cerberus detection, response, and recovery was demonstrated at the 2023 Electric Vehicle Secure Architecture Laboratory Demonstration (EV SALaD) of cybersecurity best practices, funded by DOE's Office of Cybersecurity, Energy Security, and Emergency Response in partnership with PNNL and SNL. Cerberus also earned a 2023 R&D 100 Award. The Cerberus system significantly advances the security and resiliency of high-power DC charging infrastructure by preventing or greatly reducing the potential impact severity anomalous events, therefore improving customer/user confidence, and reducing potential negative grid impacts.

Future research focuses on V2X (bidirectional charging) cybersecurity since the added complexity of bidirectional charging also significantly increases the potential security vulnerabilities.



The Cerberus SIS integrated at a high-power charge site for security and resiliency against malicious and anomalous events

Photos: INL

The 2023 EV SALaD demonstration of cybersecurity best practices for high-power EV charging infrastructure, which utilized the Cerberus SIS detection, response, and recovery performance

INVENTORY OF PUBLIC KEY CRYPTOGRAPHY (PKC) IN THE UNITED STATES INFORMS POST-QUANTUM CRYPTOGRAPHY (PQC) PREPARATIONS FOR EV CHARGING

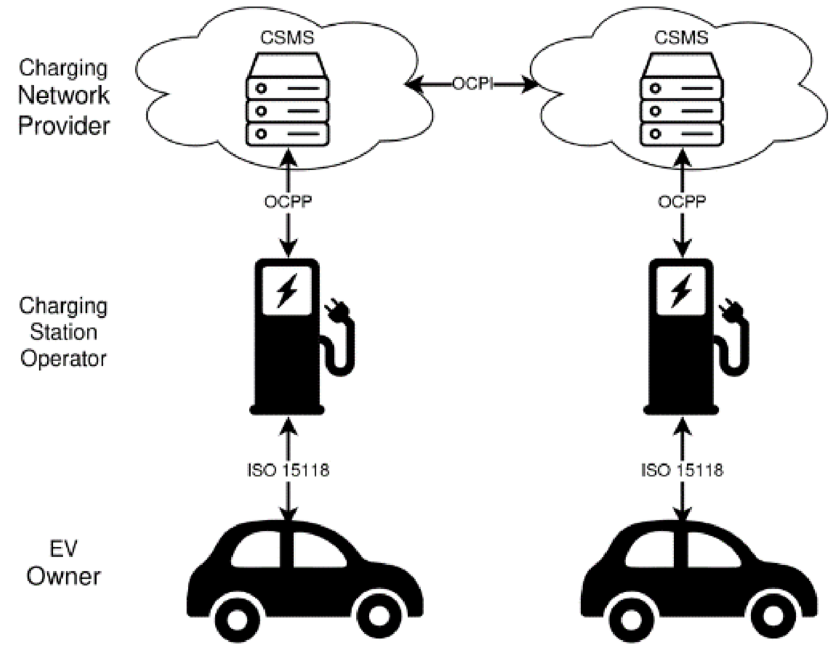
Achievement: Inventoried public key cryptosystems and applications in the EV charging infrastructure and identified potential consequences of leaving EV charging systems vulnerable to quantum computing.

Impact: Informs the EV charging stakeholders of preparations necessary for an orderly and timely migration to post-quantum cryptography—quantum-resistant cryptography that is designed to be secure against both traditional and quantum computing threats.

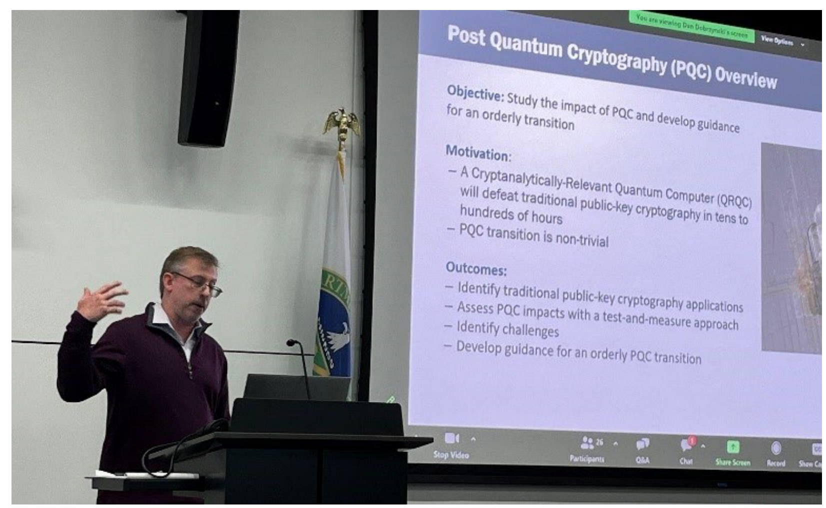
Researchers at PNNL are investigating an orderly migration to PQC for the EV charging industry. EVs and their charging infrastructure are networked systems, which employ high-level communications in support of charging and grid service decisions.

PKC underlies much of the security and privacy protections of the information exchanges. Large-scale quantum computing will be able to efficiently attack traditional PKC, potentially breaking the cryptosystems in tens of hours, compared to traditional computing efforts that demands more than 10^{18} years.

While the time to realize a quantum threat is unknown, migration from traditional PKC to quantum-resilient PQC is a global undertaking and likely represents the largest transition in computing history. The first step of preparation is understanding traditional public key applications and algorithms in EV charging. To this end, PNNL has released *Inventory of Public Key Cryptography in US Electric Vehicle Charging* (PNNL-34843), a report intended to provide the vehicle manufacturers, charging station manufacturers, charging station operators, charge network providers, and other stakeholders with information on traditional PKC applications and the potential risks to their systems if one of the algorithms is attacked.



All stakeholder relationships within EV charging infrastructure are associated with the protocols ISO 15118, OCPP, or Open Charge Point Interface.



Photos: PNNL

Researchers at PNNL are investigating an orderly migration to PQC for the EV charging industry

Electric Vehicle Charger Security Product Database

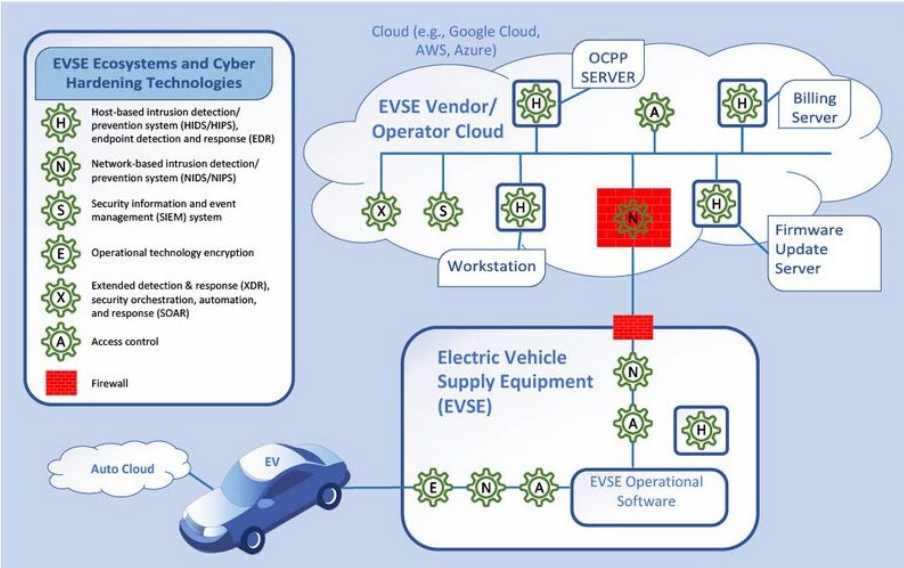


Photo: NREL

The web project is encouraging a defense-in-depth approach to EVSE security by organizing potential solutions toward the applied needs and using assessment tools to measure progress and value of those integrated outcomes

DEVELOPMENT OF EVSE SYSTEMS SECURITY SOLUTIONS ENCOURAGES DEFENSE-IN-DEPTH APPROACH TO EVSE SECURITY

Achievement: Designed and deployed a wiki-based web platform for interacting with cybersecurity companies with the potential to enhance EVSE systems. The team then drafted an EVSE-specific security controls catalog to be integrated with the Distributed Energy Resource Cyber Framework (DER-CF) tool.

Impact: The project is encouraging a defense-in-depth approach to EVSE security by organizing potential solutions toward the applied needs and using assessment tools to measure progress and value of those integrated outcomes.

Several hundred companies are developing EVSE technology to serve the mobility sector's electrification transition needs. Prior work suggests that the vendors need system-integrated options to enhance cybersecurity of the components deployed and to be deployed in the future. This project organizes available cybersecurity tools by the function they provide toward achieving cybersecurity defense-in-depth strategies for EVSE. It sets the foundation for deployment case studies and measured improvements to EVSE systems security.

Enhancing cybersecurity of EVSE can be achieved by both measuring the existing approach to security while organizing the tools and options that make defense-in-depth and cyber-informed engineering deployment methods easier for EVSE vendors and operators.

During the past year, the research team designed and deployed an initial dataset of cybersecurity tools and highlighted the needs specific to EVSE systems. NREL and SNL collaborated on this initial deployment into OpenEI. NREL then focused on drafting a catalog of controls that will be used within the DER-CF tool for guiding a prioritized deployment of the cyber solutions.

Our project outcomes will encourage more secure charging stations to penetrate the market soon by guiding prioritization and cyber strategy.

In the coming year, we will complete an EVSE security controls catalog linking risks and mitigations and then pursue industry collaboration to test its use to determine solution prioritization.

PROTOTYPE OF ZERO-TRUST PROTOTYPE DESIGNED TO SECURE EV CHARGING INFRASTRUCTURE VALIDATED

Achievement: Validated proposed zero-trust architecture, providing a model of how charging stations can be secured with commodity devices and existing frameworks.

Impact: As the first to prototype a zero-trust approach that has been tailored to secure charging station networks, provides a blueprint for others to follow in the integration of zero-trust in networks that do not necessarily fit that of a traditional enterprise network.

PNNL conducted the initial evaluation of a zero-trust prototype designed to secure EV charging infrastructure. The focus of the testing was network communication use cases. Based on lessons learned from INL's AcCCS tool and Log4J vulnerability demonstrations, the use cases and criteria were designed to study the benefit of a comprehensive zero-trust strategy to manage both network (internet) and charger adjacent vulnerabilities. While an attacker utilizing an internet pathway is the typical consideration when modeling threats, these threats show that an attacker capitalizing on the trust of an authorized charger is a pathway that must also be seriously considered and managed to limit the scope of compromise. Analysis of the evaluation results provided insights on how network communications can be further controlled and fine grain segmented to enable only the necessary communications that a charger would enact.

The milestone success was built on two key accomplishments. The first was understanding the vulnerabilities of the existing EV infrastructure and the pathways used to exploit them. Analysis of vulnerabilities and threat models published by the EVs@Scale consortium informed the security objectives, which were then mapped to security controls operating within a conceptual architecture. The second key accomplishment was prototyping the architecture with additional solutions. This milestone furthered progress by validating working zero-trust architecture, implementing controls to assist in the gaps that zero-trust have not fully addressed, and demonstrating the architecture. PNNL was able to show, using Linux capabilities with secure edge gateway devices, that networks can be segmented per interface and that communications can be controlled by only forwarding those requests targeting services in the wider zero-trust fabric. Only at that point may traffic hit the internet, which is tunneled and confined by the policies set in place in the zero-trust controller and enforced at the zero-trust edge routers. The architecture was validated through a series of tests that included ensuring chargers could not communicate with each other despite being on the same physical router, chargers could not reach any internet service unless defined by policy, and that chargers can reach critical services through the zero-trust fabric where said critical services are "dark" and unreachable via the internet (outside zero-trust fabric).

Generally, zero trust is targeted to companies and their use of cloud resources. This work is the first to prototype a zero-trust approach that has been tailored to secure charging station networks. Documentation and guidance are usually too vague or too specific in a certain solution and do not provide the means for addressing how zero-trust can be integrated into networks that aren't traditional enterprise or IT. Our work provides a model and addresses some of the gaps in existing zero-trust guidance currently provided. Furthermore, we address high-consequence events, identified by INL on prior VTO work, that may exist in charging station networks.

PNNL worked with Cisco to identify a methodology for this approach. PNNL was able to validate our proposed zero-trust architecture and model through this framework. This milestone is important because we provide a blueprint for others to follow in the integration of zero-trust in networks that do not necessarily fit that of a traditional enterprise network. Furthermore, we provide a model of how charging stations can be secured with commodity devices and existing frameworks.

This evaluation is the first of many planned to study differences in zero-trust approaches and identify gaps.

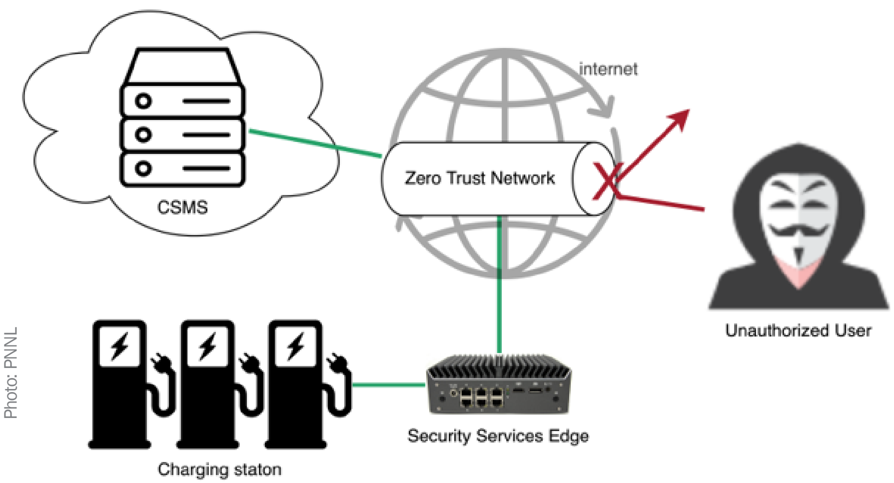


Photo: PNNL

Zero-trust fabric through which authorized entities such as the charging stations may communicate to the charging station management system while keeping unauthorized users out. Security service edge offers enhanced protection to mitigate high-consequence events.

DEVELOPMENT OF CYBERSECURITY RESPONSE & RECOVERY METHODOLOGIES FOR HIGH-POWER DC CHARGING INFRASTRUCTURE FILLS KNOWLEDGE GAP

Achievement: Developed an EV charging depot simulator to test and enhance the resilience of electric supply, EV charging infrastructures, and EV fleets against hazards such as extreme weather and cyberattacks.

Impact: Engineered a tabletop EV charger emulator, allowing for efficient experimentation without the need for real vehicles and charging stations, reducing costs, space, energy, and complexity for research.

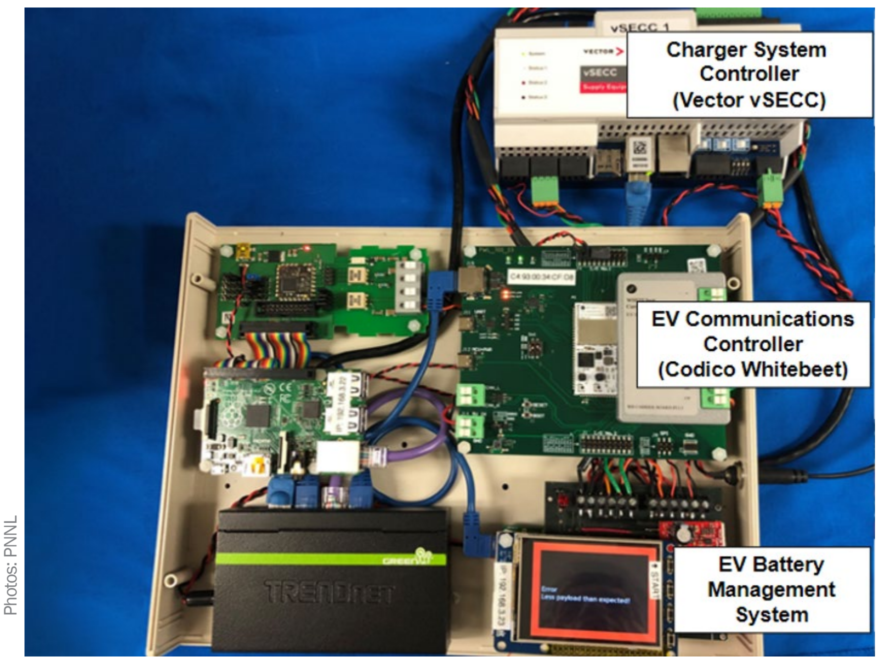
One of the main goals of the eVISION project is to develop approaches to enhance EV charging depot resiliency. Resiliency in this context is to ensure EV charging operations in the face of human and nonhuman hazards, including such events as extreme weather and cyberattacks. To identify and evaluate such methods, the experimentation of charging stations and EVs is required. Experimenting with real-world vehicles and infrastructure takes time and resources. To address this challenge, the researchers and engineers at PNNL have created an EV charging depot simulator to simplify such experimentation. It comprises a table-top fast charging emulator, representing an EV and a charging station, and a charging depot simulator, which simulates a charging depot scenario. By utilizing this, the team is able to forgo the requirements of using actual charging stations and EVs. Thus, researchers can focus more on eVISION's goal without worrying about extra cost, space, and complexity. This portable capability can be used in any test space with available power, bringing the test bed to the researcher for experimentation. This was demonstrated on Sept. 28, 2023, at the DOE VTO Semiannual Stakeholder Meeting.

The charging station depot simulator models a virtual charging depot servicing a fleet of virtual electric freight vehicles. The simulator has the capability to model and study the response to hazards, including grid anomalies—such as blackouts—and cyberattack impacts. To further increase the simulation fidelity, PNNL elected a controller hardware-in-the-loop simulation approach. PNNL developed a tabletop charging station emulator, comprising off-the-shelf components common to the vehicle and charging stations. The point of the charging station emulator is to reduce the complexity in developing and evaluating approaches to controlling charging stations without incurring the costs typically involved with experimenting with real-world chargers. One component of the emulator is a charging system controller, the computer "brains" of a charger. PNNL developed an interface so that the simulator's virtual charging depot controllers are able to control and receive events from the charging station using the OCPP, the de facto protocol governing the charging-station-to-charging-station management system communications. With this setup, PNNL has demonstrated resilience strategies that incorporate power curtailments and observe the emulator's EV component reports a decrease in charging rate.

Next steps would be to fine-tune the simulation process of the emulator and add a user-friendly interface to test different parameters and high-consequence scenarios as well as view the simulation process. Additionally, considerations are being made to emulate power electronics and submetering communications.

The charging emulator was demonstrated at the VTO Semiannual Stakeholder Meeting on Sept. 28, 2023.

Photos: PNNL



The PNNL EV and EV charger emulator components

Codes and Standards

CONSORTIUM AIDS DEVELOPMENT OF MEGAWATT CHARGING STANDARDS J3271 MCS FOR MEDIUM-DUTY AND HEAVY-DUTY VEHICLES

Achievement: Serving as chair of the SAE J3271 MCS task force since it was formed in 2021, conducted numerous tests in support of the standard and technical information reference documents.

Impact: SAE J3271 helps meet the unique high-reliability expectations for commercial vehicles, proposed as >99.99% success rate for startup on the first attempt with uninterrupted completion.

Medium- and heavy-duty commercial vehicles need megawatt-level charging to recharge quickly and avoid costly downtime. The SAE J3271, also called the Megawatt Charging System (MCS), aims to meet the unique high-reliability expectations for commercial vehicles (proposed as >99.99% success rate for startup on the first attempt with uninterrupted completion).

Currently, high-power charging for medium- and heavy-duty EVs today is solely based on SAE J1772-CCS for DC charging up to 920-V/500 A using powerline communication for signaling. To satisfy market demand, the Charging Interface Initiative (CharIN) launched the Megawatt Charging System Task Force in 2018 with three system design iterations that resulted in a final 1250-V/3000 A design that met the recommendations and requirements of the CharIN MCS. ANL staff has served as chair of the SAE J3271 MCS task force since it was formed in 2021.

The J3271-V0 Technical Information Reference (TIR) document, which describes the megawatt-level DC charging system requirements for couplers/inlets, cables, cooling, communication and interoperability, was released in December 2022. The J3271-V1 TIR was released December 2023, and J3271-V2 TIR is expected in June 2024. The Recommended Practice (RP) document requires more validation testing than an information reference document. Noise and communication interference testing was completed at BTC Power on their 3000 A EVSE to a resistive load in 2023.

NREL has completed its fourth MCS evaluation event to help develop thermal interoperability evaluation of different manufacturers' connectors and inlets to ensure they stay below safe temperature thresholds during charging; mechanical evaluations of connectors' touch safety and required insertion and withdrawal force; and validation of a reference device that will provide a standard benchmark to evaluate current and future connectors.

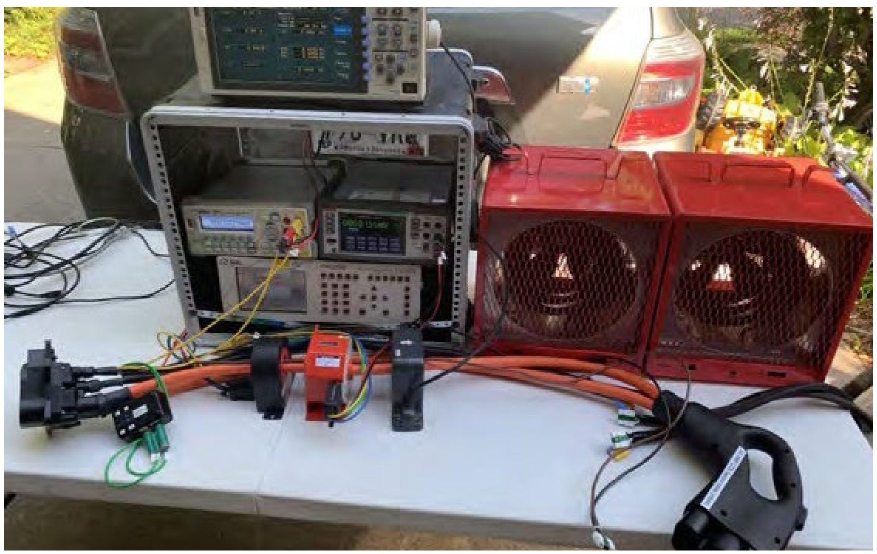
The evaluation results have been delivered to manufacturers so they can refine their designs, and an anonymized report is being delivered to support SAE J3271 and IEC 63379.

Next EVs@Scale industry partners have provided three J3271 MCS inlets (1500 A, non-cooled) and three connectors/cables (500 A, non-cooled) from Amphenol, Rema and T.E. for interoperability testing. Further communications testing with production cables is planned for spring 2024 with open-source reference design communication controller modules. There are an estimated eight J3271 connector manufacturers and eighteen MCS EVSE manufacturers working on products for release in 2024. The J3271 Recommended Practice document is expected to be published by the end 2024, pending testing.

Photo: ANL

SAE J3271, also called the Megawatt Charging System (MCS), aims to meet the unique high-reliability expectations for commercial vehicles.

The ANL team drafted an experiment plan that was peer reviewed with stakeholders, and set up the test equipment and software, test article meters, and field test EVSE according to the plan.



The consortium team conducted 25 total test articles with three redundant reference meters yielding 1,800 measurement points. Reports were released at the 6-month and 12-month test results.

Photos: ANL

LIGHT-DUTY EV CHARGING LANDSCAPE CHANGES FOR J3400 NACS AND WEIGHTS & MEASURES ADVANCE INDUSTRY-STANDARD APPROACHES

Achievement: Completion of a meter drift study to understand real-world variability of AC and DC meters for EVSEs.

Impact: Resolution of metrology methods for a consistent approach to the sale of electricity to EVs will be crucial to a robust public charging network.

The EVs@Scale consortium and industry collaborators are actively participating in the development of a majority of relevant light-duty EV charging standards. In October 2022, Tesla released the TS-0023666 connector specification called the North American Charging Standard (NACS). In early 2023, North American original equipment manufacturers announced vehicles using this specification for 2025 EVs that led to a cascade of others following suit. The SAE J3400 NACS standard work group was launched June 2023, with the TIR document published December 2023, available on SAE's website. Weekly meetings will continue in 2024 leading to the recommended practice version targeted for June 2024.

The ANL-led SAE J3400/1 task group on Combined Charging System (CCS)-NACS charging adapter safety was launched in December 2023, with TIR publication expected in June 2024. Adapters are considered a bridge solution for CCS vehicles to access existing NACS stations until more purpose-built non-Tesla NACS vehicles are deployed. Dual-output CCS-NACS EVSE is expected to be deployed in 2024.

ANL has led the Weights and Measures technical committees for the past 12 years, leading to publication of NIST Handbook 44-3.40 for commercial dispensing of electricity as a fuel in 2016 for AC and DC charging. There is currently no dataset to inform appropriate reinspection intervals for commercial EVSE. In 2023, ANL launched an ambitious meter drift real-world variability study with 9 AC and 9 DC EVSE in the field and 7 meters on the bench for 25 total test articles measured monthly to create such a dataset for reinspection intervals. The goal of this data collection is to show the lack of real-world EVSE meter accuracy drift over time using sets of high-resolution reference meters in parallel for higher repeatability. Several insights have been gained during the first 6 months of testing. Extreme cold weather affected test equipment performance more than EVSE that is designed for these conditions (−16°F). Test-to-test repeatability is less than desired and somewhat influenced by limited resolution of EVSE data. DC measurements via EV-as-a-load with a pass through cable are time-consuming (time to discharge vehicle pack to low state of charge) and less repeatable than using an adjustable load bank. ANL has also worked with a NIST committee (not NCWM) on a Handbook 105-related special publication (SP2200-4) related to SI traceability of transfer standards used to verify calibration of field test equipment for EVSE testing.

Publicly Available Tools and Data

Many EVs@Scale accomplishments have been made possible by the team's development of new capabilities, numerical algorithms, and computational tools. The consortium is developing a tool kit inventory with user-friendly versions of models that will be developed and made publicly available to support stakeholder planning activities. The following data and tools can be accessed online by the wider research community.

Access capabilities through CCS communications protocol (AcCCS)
https://inlsoftware.inl.gov/product/access-capabilities-through-ccs-communications-protocol-acccs
INL's AcCCS is a collection of tools and scripts that emulate EV communication controllers and EVSE communication controllers. It utilizes open-source code, off-the-shelf hardware, and published protocol specifications to create a versatile and cost-effective test and evaluation device for the Electric Vehicle industry.

Cerberus
https://inlsoftware.inl.gov/product/cerberus
INL's SIS for Extreme Fast Charging (XFC) Infrastructure (Cerberus) tool is responsible for gathering data from multiple sources to monitor the safety and security properties (cyber and physical) of multiple XFC. The data are processed and analyzed by software running on the SIS Core and SIS Aggregator systems.

Distributed Energy Resource Cyber Framework (DER-CF)
https://dercf.nrel.gov/
NREL's DER-CF is a no-cost, interactive web tool that holistically evaluates a facility's distributed energy resource cybersecurity posture—or health—and makes customized recommendations.

Electric Vehicle Infrastructure – Energy Estimation and Site Optimization Tool (EVI-EnSite)
https://www.nrel.gov/transportation/evi-ensite.html
NREL's EVI-EnSite is a charging station design, modeling, and analysis tool. Researchers use EVI-EnSite to conduct studies that need flexible simulations for light-, medium-, and heavy-duty EV charging at different charging station configurations—from low-power charging scenarios (i.e., Level 1 and Level 2) to high-power, DC fast-charging (DCFC) stations at the multimegawatt scale.

Electric Vehicle Infrastructure – Projection Tool (EVI-Pro)
https://www.nrel.gov/transportation/evi-pro.html
NREL's EVI-Pro, developed in collaboration with the California Energy Commission, draws on detailed data about personal vehicle travel patterns, EV attributes, and charging station characteristics to estimate the required quantity and type of charging infrastructure.

Photos (left to right): ORNL, INL PNNL

Selected Publications and Notable Presentations

EVs@Scale Lab Consortium Semiannual Stakeholder Meeting at Oak Ridge National Laboratory – B. Ozpineci, M. Weismiller, L. Slezak, A. Meintz, J. Bennett, J. Kisacikoglu, D. Dobrzynski, B. Carlson, K. Davidson, O. Onar, V. Galigekere, B. Carlson, M. Starke, T. Carroll, T. Bohn, 2023. https://evsatscale.ornl.gov/wp-content/uploads/2023/04/EVs@Scale-Consortium-Bi-Annual-Stakeholder-Meeting_April-2023.pdf

EVs@Scale Lab Consortium Semiannual Stakeholder Meeting at Argonne National Laboratory – A. Meintz, J. Kisacikoglu, S. Thurston, B. Carlson, M. Starke, T. Carroll, J. Bennett, J. Denney, J. Harper, A. Ali, M. Chinthavali, P. Kandula, V. Galigekere, D. Stanton, T. Bohn, A. J. Palmisano, P. Thompson, R. Kaiser, P. Stith, 2023. https://www.nrel.gov/docs/fy24osti/87781.pdf

Electric Vehicles at Scale (EVs@Scale) Laboratory Consortium Deep-Dive Technical Meeting: Smart Charge Management and Grid Integration May 18, 2023 – J. Harper, S. Ghosh, M. Zhang, M. Sundarrajan, J. Lohse, C. Edie, 2023. https://www.nrel.gov/docs/fy23osti/86457.pdf

Data-driven method for electric vehicle charging demand analysis: Case study in Virginia – Z. Liu, B. Borlaug, A. Meintz, R. Zeng, C. Neuman, E. Wood, J. Bennett, 2023. https://doi.org/10.1016/j.trd.2023.103994

Grid Impact Analysis and Mitigation of En-Route Charging Stations for Heavy-Duty Electric Vehicles – X. Zhu, P. Mishra, B. Mather, M. Zhang, A. Meintz, 2023. https://doi.org/10.1109/OAJPE.2022.3233804

Performance and Implementation Requirements for Residential EV Smart Charge Management Strategies – M. Sundarrajan, J. Bennett, D. Scoffield, K. Chaudhari, A. Meintz, T. Pennington, B. Zhang, 2023. https://doi.org/10.1109/ITEC55900.2023.10186998

Photos (top to bottom): PNNL, NREL

Photos (top to bottom): ANL, ORNL

Electric Vehicles at Scale (EVs@Scale) Laboratory Consortium Deep-Dive Technical Meetings: High Power Charging (HPC) Summary Report – A. Meintz, L. Slezak, J. Kisacikoglu, S. Thurston, B. Carlson, A. Thurlbeck, P. Kandula, B. Rowden, M. Chinthavali, R. Wojda, J. Harter, S. Campbell, C. Boone, A. Ali, E. Ucer, 2023. https://www.nrel.gov/docs/fy23osti/86407.pdf

NextGen Profiles High Level Analysis & Procedures Report –K. Davidson, N. Kogalur, I. Tolbert, E. Watt, A. Meintz, 2023. https://www.nrel.gov/docs/fy24osti/88898.pdf

NextGen Profiles EVSE Characterization Report – R.B. Carlson, O. Onar, 2023. https://doi.org/10.2172/2328073

NextGen Profiles EV Profile Capture Report – S. Thurston, L. Wells, 2023. https://www.osti.gov/biblio/2293478

NextGen Profiles Fleet Utilization Report – L. Wells, S. Thurston, 2023. https://www.osti.gov/biblio/2293479

High-Power Electric Vehicle Charging Hub Integration Platform (eCHIP) - Design Guidelines and Specifications for DC Distribution-Based Charging Hub – J. Kisacikoglu, J. Harper, R. P. Kandula, A. Thurlbeck, A. Ali, E. Ucer, E. Watt, M. S. Khan, R. Mahmud, 2023. NREL/TP-5400-86326

Inventory of Public Key Cryptography in US Electric Vehicle Charging – T. Carroll, L. Redington, A. Moran-Schmoker, A. Murray, 2023. https://www.osti.gov/biblio/2204867

EVs@Scale Lab Consortium Deep-Dive Technical Meetings: Codes and Standards (C&S) Presentation – T. Bohn, M. Duoba, B. Varghese, B. Dindlebeck, O. Onar, I. Tolbert, A. Meintz, C. Bernat, R. Kaiser, N. Kogalur, J. Martin, M. Mohammad, 2023. NREL/PR-5400-88363.

Acronyms and Abbreviations

ABM.................agent-based model

AC.....................alternating current

ANL...................Argonne National Laboratory

CCS...................Combined Charging System

DC.....................direct current

DOE..................U.S. Department of Energy

eCHIP..............High-Power Electric Vehicle Charging Hub Integration Platform

EV.....................electric vehicle

EVs@Scale.......Electric Vehicles at Scale

EVSE.................electric vehicle supply equipment

FY......................fiscal year

INL....................Idaho National Laboratory

LBNL.................Lawrence Berkeley National Laboratory

MCS...................Megawatt Charging System

NACS................North American Charging Standard

NREL...............National Renewable Energy Laboratory

OCPP...............Open Charge Point Protocol

ORNL...............Oak Ridge National Laboratory

PKC...................public key cryptography

PQC...................post-quantum cryptography

PNNL...............Pacific Northwest National Laboratory

SCM.................smart charge management

SIS....................safety instrumented system

SNL...................Sandia National Laboratories

TIR.....................technical information reference

TOU...................time of use

V2X...................vehicle-to-everything

VGI.....................vehicle-grid integration

VTO...................Vehicle Technologies Office

Photos (top to bottom): PNNL, NREL

EVs@Scale Team

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