EVs@Scale
U.S. Department of Energy

NextGen Profiles

High Level Analysis & Procedures Report

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Disclaimer

Authors

The authors of this report are:

Keith Davidson, National Renewable Energy Laboratory (NREL)

Namrata Kogalur, National Renewable Energy Laboratory NREL)

Isaac Tolbert, National Renewable Energy Laboratory (NREL)

Ed Watt, National Renewable Energy Laboratory (NREL)

Andrew Meintz, National Renewable Energy Laboratory (NREL)

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Contributors:

Lee Slezak, Department of Energy – Vehicle Technologies Office (VTO)

Daniel Dobrzynski, Argonne National Laboratory (ANL)

Landon Wells, Argonne National Laboratory (ANL)

Sam Thurston, Argonne National Laboratory (ANL)

Benny Varghese, Idaho National Laboratory (INL)

Richard “Barney” Carlson, Idaho National Laboratory (INL)

Omer Onar, Oak Ridge National Laboratory (ORNL)

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List of Acronyms

A	Ampere
AAC	Ampere, Alternating Current
ADC	Ampere, Direct Current
AC	Alternating Current
DC	Direct Current
CHAdeMO	Charge de Move; Japanese DC charging standard
CCS	Combined Charging System
CCS1	Combined Charging System, Type 1 (North America)
CCS2	Combined Charging System, Type 1 (European)
DOE	U.S. Department of Energy
EM	Electromagnetic
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
GB/T	国标推荐 (Guóbiāo/Tuījiàn, Chinese recommended/voluntary national standard)
HEV	Hybrid Electric Vehicle
HPC	High Power Charging
HZ	Hertz
IEC	International Electrotechnical Commission
KW	Kilowatt
MCS	Megawatt Charging Standard
MW	Megawatt
NACS	North American Charging Standard
NEMA	National Electrical Manufacturers Association
NGP	NextGen Profiles
NiMH	Nickel Metal Hydride
OCPP	Open Charge Point Protocol
OEM	Original Equipment Manufacturer
P	Real Power
PF	Power Factor
PHEV	Plug-in Hybrid Electric Vehicle
Q	Reactive Power
S	Apparent/Complex Power
SAE	Society of Automotive Engineers
SCM	Smart Charge Management
SCMS	Smart Charge Management System
SOC	State of Charge
THD	Total Harmonic Distortion
V	Volts or Voltage
VAC	Volts Alternating Current

VDC	Volts Direct Current
V2X	Vehicle-to-Everything
WPT	Wireless Power Transfer
XFC	eXtreme Fast Charge

Executive Summary

As part of the U.S. DOE EVs@Scale consortium, the *NextGen Profiles (NGP)* project presents analysis and results from the study of High Power Charging Electric Vehicles and Battery Charging Infrastructure. High Power Charging equipment is capable of recharging electric vehicle traction batteries at power levels of 200KW and above.

The NextGen Profiles project has three pillars of investigation: Electric Vehicle Charging Profile Capture, Electric Vehicle Service Equipment Performance Characterization and Fleet Utilization analysis. All NextGen Profiles project testing was conducted under test conditions that comprise a diverse range of realistic real-world operating conditions including nominal conditions that should transfer the maximum allowable energy in the minimum time possible and off-nominal conditions that typify charging performance under suboptimal charging conditions. Results from 13 unique EVs, eight EVSEs and four electrified fleets are included in the NextGen Profiles project analysis.

Findings from the NextGen Profiles project are broken out into four reports. *EV Profile Capture: A NextGen Profiles Project Report* details test data, outcomes and evaluation related to EV charging profile capture. *EVSE Characterization: A NextGen Profiles Project Report* details test data, outcomes and evaluation related to EVSE performance characterization. *Fleet Utilization: A NextGen Profiles Project Report* details insights from case studies of EV and EVSE fleet utilization. This *High Level Analysis & Procedures: A NextGen Profiles Project Report* summarizes the electrified mobility charging landscape, NextGen Profiles testing procedures and findings detailed in the other three reports.

The results published in the series of NextGen Profiles project reports provide data and insight for use by numerous entities including modeling and simulation organizations, policy makers, fleet planners and industry stakeholders among others involved with the development and deployment of electrified transportation technologies. Additional high-power conductive and wireless charging results are anticipated in future publications in support of the U.S. DOE EVs@Scale consortium NextGen Profiles project.

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1.1 Overview of Charging Levels

As the transportation sector rapidly electrifies, a robust demand for electric charging infrastructure is created that, for the general public, has similar performance and is familiar in operation and user experience as compared to liquid fueling stations (Meintz, et al. 2017). The SAE J1772 EV and PHEV conductive charging standard defines two AC and two DC conductive methods to transfer energy and charge a vehicle battery. SAE J2954 is the SAE standard for wireless vehicle charging.

The NextGen Profiles project focuses on the North American region electrified transportation market.

1.1.1 AC Level 1 Charging

AC Level 1 charging provides energy from a (North American) single phase 120VAC 60Hz electrical circuit to an EV or PHEV traction battery. The most common electrical receptacles for AC Level 1 charging are NEMA 5-15R for 15A circuits and NEMA 5-20R for 20A circuits. AC Level 1 charging uses onboard vehicle electronics to convert AC power into DC power at levels below 2KW (SAE International 2017). AC charging methods are not in scope for the NextGen Profiles Project.

1.1.2 AC Level 2 Charging

AC Level 2 charging provides energy from a (North American) single phase 208VAC or 240VAC 60Hz electrical circuit at or below 80A continuous to an EV or PHEV traction battery. AC Level 2 charging uses onboard vehicle electronics to convert AC power into DC power at levels below 20KW (SAE International 2017). AC charging methods are not in scope for the NextGen Profiles Project.

1.1.3 DC Level 1 Charging

DC Level 1 charging provides energy at or below 1000VDC and 80A continuous to an EV or PHEV traction battery. DC Level 1 charging bypasses onboard vehicle electronics as grid AC power is converted into DC power from dedicated service equipment at levels below 80KW via the 5-pin J1772 connector (SAE International 2017). DC Level 1 charging methods are not commonly implemented and not in scope for the NextGen Profiles Project.

1.1.4 DC Level 2 Charging

DC Level 2 charging provides energy at or below 1000VDC and 400A continuous to an EV or PHEV traction battery. Commonly (and incorrectly) referred to as Level 3 charging, DC Level 2 charging bypasses onboard vehicle electronics as grid AC power is converted into DC power from dedicated service equipment at levels below 400KW via the 7-pin CCS1 connector in North America (SAE International 2017).

DC Level 2 charging is commonly referred to as DC Fast Charging. EVs or EVSEs capable of facilitating battery charging at powers of 200KW and above are considered High Power Charging (HPC) equipment. EVs or EVSEs capable of facilitating battery charging at powers of 350KW and above are considered eXtreme Fast Charging (XFC) equipment. DC Level 2 charging methods are the focus of the NextGen Profiles project.

1.2 Advantages and Disadvantages of DC Level 2 Charging

1.2.1 Advantages of DC Level 2 Charging

Although electric vehicles are generally more energy-efficient than liquid-fueled vehicles, operating an EV is still extremely energy-intensive. DC Level 2 Charging affords drivers a convenient option to "top up" their vehicle battery on short stops, during long distance trips and in high-traffic areas. DC Level 2 Charging technologies that mimic the user experience of liquid fueled vehicles improve the convenience and reduce the challenges associated EV operation and make electrified mobility economically competitive in many use cases that would otherwise be infeasible due to downtime required to charge the traction battery. Similarly, electrification of medium & heavy-duty vehicle fleets would not be possible at high utilization rates without DC Level 2 Charging technologies.

Networked high power DC Level 2 Charging technologies present opportunities for delivery of grid-edge, load management and ancillary services that maximize utilization of installed grid infrastructure and minimize costs and barriers to adoption for electrified means of transportation.

1.2.2 Disadvantages of DC Level 2 Charging

One of the main drawbacks of DC Level 2 Charging is that it requires compatible hardware: not all EVs are capable of charging at rates of 200KW or above. Similarly, not all EVSEs are capable of 200+KW charging speeds; such high performance systems are not installed in many areas for myriad reasons: DC Level 2 Charging systems require a high power electrical connection to the grid to operate at rated capacity; these connections may require grid upgrades and utility permission to install and operate, DC Level 2 Charging Systems have a large installation footprint, which limits potential installation location options and DC Level 2 Charging Systems are expensive to procure and have long lead times for delivery.

Additionally, both the EV and EVSE must have a compatible charging connectors and inlets; the NextGen Profiles project primarily focused on systems that employ the 7-pin CCS standard defined in SAE J1772, but other charging systems exist, such as NACS, WPT, MCS, GB/T, CHAdeMO and ChaoJi. The *EVSE Characterization: A NextGen Profiles Project Report* includes performance details and usage characteristics of WPT systems and a future EVSE characterization report will examine the performance of NACS charging systems.

DC Level 2 Charging systems generate more heat than other charging methods, which can stress vehicle battery components and accelerate battery aging over time. Furthermore, the intense energy use of DC Level 2 Charging systems can negatively contribute to grid impacts and incur demand charges for electricity. Even without demand charges, electricity dispensed by DC Level 2 Charging systems tends to be more expensive than typical retail rates.

DC Level 2 Charging systems are very complex; many EV drivers report reliability concerns and these technologies present considerable service challenges (Chokshi 2022).

Finally, when performing an Electric Vehicle finishing charge, there is a de minimis or negative performance differential of DC Level 2 Charging Systems when compared to alternative technologies.

1.3 Focus on DC Level 2 Charging Performance Testing

The NextGen Profiles Project and this report focus on DC Level 2 charging methods that utilize the SAE J1772 7-pin CCS standard and WPT charging systems with minimum charge power capabilities of 150 – 200 KW and above.

The NextGen Profiles project is split into three distinct test categories or pillars:

- Vehicle Charge Profiles Characterization quantifies the charge power of the combination of EV and EVSE during a full charge event. This evaluation quantifies the charging characteristics across a wide range of battery SOC as well as identifies the impact of the initial battery SOC, initial battery temperature, and other boundary conditions.
- Charging Infrastructure Characterization measures the quasi-steady state performance characteristics of the HPC EVSE system across a wide voltage and current operating range. This evaluation is conducted under nominal operating conditions (grid input, ambient temperature, etc.) as well as during off-nominal conditions of ambient temperature, grid input, and energy management control.
- Fleet Charging Utilization and Characterization measures the charging operational characteristics of infrastructure utilized in fleet operations by collaborative partners.

1.4 Electric Vehicle Battery Technologies

1.4.1 Chemistry

All vehicles characterized in the NextGen Profiles project employed traction batteries that utilize lithium-ion chemistries. This is the most common type of electric vehicle battery in use today, due to the format’s light weight, safety record, long cycle life and high energy and power density.

Many different chemistries of lithium-ion batteries exist and are employed in electric vehicles today; each type has its own unique characteristics; examination of EV traction battery chemistry and design is outside the scope of the NextGen Profiles project, although it is studied elsewhere (Meintz, et al. 2017).

1.4.2 400-Volt Topology

The first modern mass-market electric vehicles utilized a 400 VDC battery pack and drivetrain because 400-volt componentry were already designed and widely available from the already-established and comparatively mature market for HEVs and PHEVs like the Toyota Prius (Agatie 2022). Consequently, fully electrified EVs were able to exploit existing economies of scale at the 400 VDC level while growing the emerging market, improving performance and driving costs down (Scott 2023). In general, when compared to the competing 800-volt architecture, the lower voltage of a 400 VDC battery pack means it presents less risk of electrocution or arc flash, requires less insulation, has lower pack leakage currents, benefits from cheaper protection circuitry and simpler protection schemes and is less impacted by a weak series-connected cell (Jenkins 2021). Most EVs on the road today employ a 400 VDC battery and drivetrain topology (Vaughan 2022).

1.4.3 800-Volt Topology

The trend towards higher voltage battery packs is driven by several factors, including the ability to deliver more power without increasing current, which can reduce copper loss, increases efficiency, saves weight thereby giving vehicle designers more freedom to balance handling, acceleration, range and cost, (Vaughan 2022) and most importantly, reduces heating which simplifies thermal management system requirements to regulate temperature, improves charging times by roughly 50% under optimal conditions (Anderson 2022) and lengthens the lifespan of the traction battery and drivetrain power electronics (Scott 2023). Even though the transition to 800-volt systems is in its early stages, it is for these reasons that many EV suppliers expect 800-volt architectures to soon become the default industry standard (Anderson 2022).

1.4.4 Boost Converter

The 800-volt EV architecture has unquestionable advantages, but a critical challenge that must be overcome to take full advantage of all the benefits of high-voltage/high-power offboard charging is making the availability of compatible charging infrastructure universal (Osmanbasic 2023). Charging speed depends on charging stations, and most, such as the Tesla supercharger network, are built to provide power for 400-volt EVs (Halvorson 2023). Until all EVSEs support high-voltage/high-power charging, the electrified mobility industry will need to undergo a period of transition. To help bridge the gap to a time when EVSEs capable of 800-volt charging are as ubiquitous as the availability of EVs with 800-volt topology, manufacturers are implementing designs that boost the output from a 400-volt-capable vehicle to charge an 800-volt battery pack such as Porsche’s onboard 400-volt/150 KW power converter or Hyundai Motor Group’s

Integrated Drive Axle (Kane 2020). While boost converters make it is possible to charge an 800-volt EV with a 400-volt EVSE, the additional hardware and vehicle design complexity may result in slower charging speeds and slightly lower efficiency when compared to charging scenarios when all equipment is rated for 800-volt charging.

2 DC Charging Technologies and Infrastructure

2.1 Interface to Grid/Utility

To provide an acceptable user experience, high power DC charging technologies for electric vehicles require a high-capacity, robust and efficient grid interface. High power DC charging systems are designed to utilize 480 VAC three-phase power connections in North America and are only located in areas where access to such electrical connections are available. These locations require either a dedicated high voltage transformer to connect to utility electrical distribution circuits or existing infrastructure with sufficient capacity to support the addition of high-power charging loads. All EVSEs characterized in this report utilize 480 VAC three-phase grid power connections.

Additional vehicle charging load can strain existing grid infrastructure as electric vehicles and electric vehicle charging equipment becomes more ubiquitous. High power DC charging technologies have the potential to exacerbate this situation because of their propensity to demand intense amounts of power for short periods of time, making it harder for grid operators to match supply and demand and increasing costs through demand charges (St. John 2015). During times of grid stress, the increased variability of electrical loading has the potential to be smoothed out and total EV charging load reduced by utilizing smart charging OCPP commands to curtail DC charging station maximum allowable charge rates. DC charging station OCPP performance is examined in the *EVSE Characterization: A NextGen Profiles Project Report*, Section 3.4.

The use of microgrids and medium voltage grid connections and DC distribution equipment to power DC electric vehicle charging is an area of active research and development (García-Trivino, et al. 2016). As such technologies are developed and deployed, utilization of DC distribution to power DC charging technologies from a medium voltage grid connection are an area to consider for inclusion in future NextGen Profiles studies.

2.2 DC Charging Station Architecture

All deployed DC charging stations today receive AC electricity from the electric grid and convert it into DC electricity that is applied to a vehicle traction battery while bypassing vehicle onboard charging electronics. The process that electricity is converted from AC to DC is proprietary based on the EVSE manufacturer's design, but generally there is an AC/DC power stage and a DC/DC power stage integrated into each station. Each converter in its power stage comprises power switches and gate drivers, current and voltage sensing, and a controller (Ramakrishnan and Rangaraju 2020).

NextGen Profiles testing characterized DC charging stations with two differing topologies for the HPC EVSE systems; shown in Figure 1. On the left of Figure 1, each power cabinet is DC coupled directly to the EVSE dispenser; this is considered a paralleled system that is coupled at the dispenser. On the right of Figure 1, the power cabinets system only has a single DC connection to the dispenser; this is considered a paralleled system that is coupled at the primary cabinet.

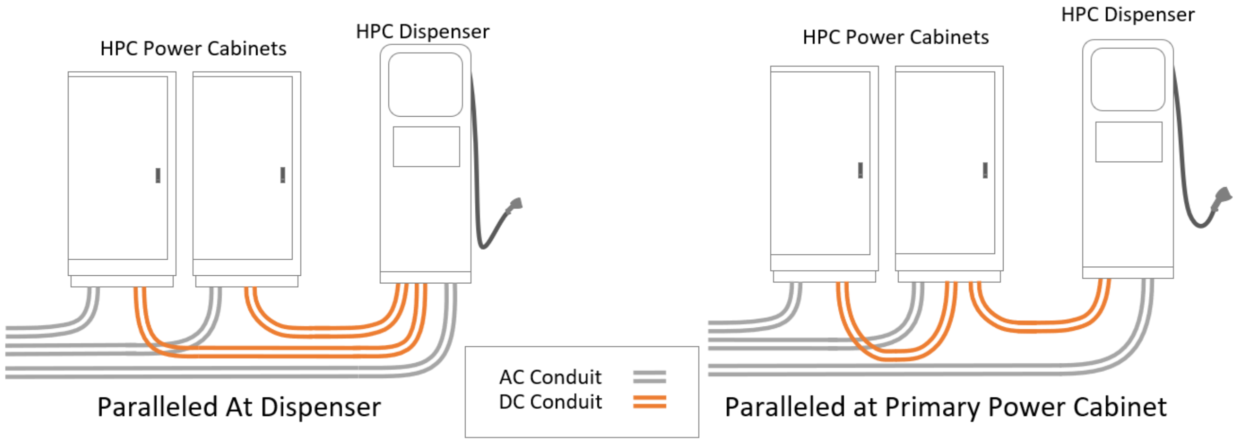

Figure 1. EVSE System Topologies

The EV driver interacts with the HPC Dispenser or Kiosk to plug in the vehicle, pay for and authorize the charge session and start the charge. NextGen Profiles Conductive EVSE Characterization and EV Charging Profile Capture testing was performed in a laboratory setting to the greatest extent possible utilizing EVSEs configured in a two-tower/one-dispenser configuration.

2.3 Connectors, Cables & Protocols

2.3.1 Combined Charging System (CCS)

The Combined Charging System (CCS) is a standard for charging EVs that was developed by major European and American automakers to create a unified charging solution for electric vehicles by using a single conductive charging port connector to perform AC or DC charging. (Schneider 2015) It is rated for 1000 VDC and can deliver up to 400 continuous amperes with a maximum output power of 400 KW (SAE International 2017). There are two types of CCS connectors: CCS Type 1 is a 7-pin plug primarily used in North America while CCS Type 2 is a 9-pin plug primarily used in Europe and other regions. All conductively charged EVSEs and most EVs evaluated in the NextGen Profiles project utilized CCS Type 1 connectors and inlets.

2.3.2 CHAdeMO

CHAdeMO is an early DC Level 2 Charging standard developed in Japan that codifies a method of bidirectional power flow, or V2X, which enables an EV to power many kinds of electrical loads (CHAdeMO 2020). The CHAdeMO 2.0 standard enables charging speeds up to 400 KW and supports PnC functionality (CHAdeMO n.d.). NextGen Profiles testing did not utilize the CHAdeMO charging system.

2.3.3 GB/T charging connector

GB/T connector is the national standard for AC and DC charging of EVs in China and is capable of charging speeds up to 500KW (EVBox 2023). Although the interface resembles the CCS Type 2 system, the pin configuration is different incompatible (EVBox 2023). NextGen Profiles testing did not utilize the GB/T charging system.

2.3.4 ChaoJi

The ChaoJi, or CHAdeMO 3.0 standard, was developed in collaboration between the CHAdeMO Association and China Electricity Council and is capable of charging speeds up to 1.2 MW (CHAdeMO 2023). NextGen Profiles testing did not utilize the ChaoJi charging system.

2.3.5 North American Charging Standard (NACS)

The NACS interface was developed by Tesla and can be found on all North American market Tesla vehicles since 2012 and was opened for use to other manufacturers in 2022 (Mobility Insider 2023). In February 2023, Tesla announced that it would open its charging network with new "Magic Dock" charging stations that include an NACS-CCS adapter built into the station charging post (Motavalli 2023). In June 2023, following announcements from major auto manufacturers that they will adopt the interface, the Society of Automotive Engineers announced that it will standardize the connector system as J3400 to ensure that any supplier or manufacturer will be able to use, manufacture or deploy NACS connectors and/or inlets (Society of Automotive Engineers International 2023). The NextGen Profiles project did not characterize the charging performance of any EVSEs using NACS connectors and EV charging profiles captured from vehicles equipped with NACS inlets was completed utilizing CCS-NACS adapters.

2.3.6 Megawatt Charging System

The Megawatt Charging System is an charging connector standard for power intensive future transportation applications that supports energy transfer at levels up to 3000ADC and 1250VDC (CharIN Charging Interface Initiative e. V. n.d.). NextGen Profiles testing did not utilize the MCS charging system.

2.4 Conductive vs Non-Conductive Charging

Conductive and wireless charging are two differentiated methods of charging electric vehicles. Conductive charging necessitates a physical connection between the power supply and the vehicle; requiring physical manipulation of charging equipment and is the dominant means employed for EV charging activities globally. Wireless charging, also known as inductive charging, offers the convenience of hands-free charging without any physical contact between the charger and the vehicle; an ideal use case for WPT is for a vehicle that makes frequent short stops at wireless charging pads to top off available range.

Analysis of conductive and non-conductive charging system performance characterization was performed using a wide range of DC output current and DC voltage charging conditions to quantify the operational performance of the EVSE at nominal and off-nominal test conditions. Conductive EVSE characterization aims to explore performance across boundary conditions pertaining to ambient temperature, AC grid input conditions, and Smart Energy Management system curtailment requests. Additionally, high-utilization testing was conducted to quantify the EVSE performance during quick succession, short-duration charge sessions at full power. For WPT, nominal test conditions are used and compared with a different set of WPT-specific off-nominal boundary conditions pertaining to misalignment and airgap scenarios between the EVSE and EV emulator coils.

3 NextGen Profiles Project Introduction

3.1 Background, Motivation & Importance

In both commercial and consumer EV segments there are concerted efforts by EV and EVSE OEMs to increase charge energy delivered while simultaneously decreasing charging time. To accomplish these goals, innovations must be made to increase the peak charging power of EVs. With HPC systems commonly exceeding 200 kW of power delivery, it is apparent that HPC profiles can vary greatly by EV. Variations in HPC profiles can also be introduced due to factors within the vehicle, such as battery SOC and battery temperature, and external factors, such as ambient temperature.

To intelligently integrate HPC systems within the grid and among co-located loads and sources it is critical to quantify and characterize the charging profiles that these systems will present. Characterizing the performance of EVs and EVSEs during HPC sessions is crucial for developing better HPC control schemes and grid energy management systems, modeling grid impacts and electrified transportation systems, optimizing battery designs, standardizing best practices and improving understanding the rapidly evolving EV charging landscape.

3.2 Project Team & Industry Relations

The NextGen Profiles project leverages laboratory team capabilities, OEM stakeholder relationships, current HPC fleet deployments, and XCEL project outputs to quantify and characterize current and next generation HPC EV profiles and EVSE characteristics.

The laboratory team consists of: Argonne National Laboratory as lead lab, National Renewable Energy Laboratory, Idaho National Laboratory, and Oak Ridge National Laboratory.

3.3 Research Objectives, Scope & Limitations

The assessment performed in the NextGen Profiles project include both conductive and inductive charging topologies from a variation of vehicle classes including light, medium, and heavy duty with minimum charge power capabilities of 150 – 200 KW and above. The objectives of the project are as follows:

- Develop Test Procedures – Collaboratively develop the test requirements, procedures, and measurement parameters for both conductive and wireless charging evaluation. The developed procedures are to be used for laboratory HPC profile capture, EVSE characterization and informs guidelines for data capture for fleet and in-field evaluations.
- Capture HPC Profiles – Develop rich profile sets from each EV project asset. Assets constitute light-duty consumer and commercial EVs that include both conductive and inductive charging. The profiles are to be gathered through a combination of in-lab

evaluations, field evaluations, and data gathering of in-use HPC EV fleets. Whenever possible, HPC profile sets include a nominal charging profile with subset profiles that are gathered during off-nominal conditions that include varied ambient temperatures, grid events, and/or managed charge control.

- Characterize HPC EVSE – To fully quantify the charging load as seen by the grid, EVSE performance characterization of power transfer, efficiency, power quality, and harmonics injection are to be conducted for laboratory DC charging stations across the rated operating ranges and with next generation HPC profiles. These characterization measurements focus on quantifying the efficiency, power quality, harmonics, thermal management operation and response to smart charging commands. Characterization across the full operating range of XFC will eliminate the need for assumptions and extrapolation from the limited XFC operational data currently available.
- Fleet Utilization Analysis – Investigate electrified fleet employment trends to balance operational scheduling with the constraints of fleet electrification with a goal of expanding electrified fleet employment through optimizations identified through data analysis to lower ownership costs and minimize associated grid impacts. This report gleans utilization insights of EV and EVSE fleets by providing case study analysis; external sensors and onboard telematics are used to understand the behaviors and utilization of fleet vehicles and charging equipment.
- Integrate, Analyze, and Report Data – Evaluation outputs and data collection to be shared publicly and among project partners. Data analysis will be required throughout the project for interim reporting and to ensure all shared data is of requisite quality. Late-stage analysis will be conducted to report outcomes and findings of the resulting data. Results and data will be directly provided to modeling teams upon request.

The scope and limitations of the project are as follows:

- Procedure Development – National laboratory teams collaboratively develop the test requirements, procedures, and measurement parameters for both conductive and wireless charging evaluation, including the definition of nominal conditions as well as developing the factors for in-depth laboratory investigations. The NextGen Profiles project team will solidify the minimum measurement requirements and calculated parameters that will be generated from evaluations as a primary output from this project prior to procedure execution. Project collaborators and industry partners will be queried for input and feedback on the measurements, calculated parameters, procedures, and process of the characterization.
- HPC EV Profile Capture and EVSE Characterization – The NextGen Profiles project team independently aligns resources and leverages relationships to line up a wide breadth of HPC EV and EVSE assets capable of HPC. These assets include partner laboratory

resources, OEM partner share, OEM and laboratory field evaluations, in-use and planned fleet EV/EVSE, and use of XCEL research profiles. For the duration of the project, the project team continues outreach to existing and emerging potential partners as the electric vehicle and infrastructure landscape changes.

- Evaluation Methodology – The NextGen Profiles project team determines baseline HPC EV and EVSE equipment characteristics and charge profiles during the procedure-defined nominal test conditions. Off-nominal conditions testing must follow procedure to set initial test conditions such as EV/battery conditions, ambient temperature, grid conditions, and charge management controls to observe how HPC profiles and equipment characteristics are affected by factors or factor combinations. The combination of these characterizations will allow evaluation of HPC EV and EVSE metrics that include overall charging load profile, EV and EVSE thermal management loads, EV and EVSE charging efficiency, ramp rates, peak power, power quality, and external factor effects.
- Dissemination and Reporting - Datasets and project outputs will be made available for use by other research groups, grid planners, OEMs, and various other project participants and industry stakeholders. For the project results to be useful the datasets need to be clear, comprehensive, and consistent; the project team performs regular data quality checks to ensure data from multiple sources are aggregated in identical formats using common labels to ensure that use of the datasets has low thresholds and can produce effective research and planning.

3.4 Project Outputs & Data Sharing

Three results output categories were defined to maximize the utility of test data to the public and research partners, while also protecting proprietary and/or business-sensitive information:

- Public Results - The public results category consists of high-level, anonymized test results which are published without restriction. These results are focused on maximum, minimum, and average metrics, as well as high-level graphs to convey the overall performance characteristics of high-power charging profiles. The public results detail the performance of a specific anonymized vehicle with a specific anonymized EVSE, including charge event efficiency, peak charge power, and average power quality (power factor, current total harmonic distortion, etc.). To promote analysis between and within external groups, the public results may disclose details of the EV or EVSE that are relevant to results dissemination, including vehicle classes of the EV (e.g. light, medium, or heavy-duty), charging power capability of the EVSE (350 kW, 500 kW, or 500+ kW), and charging medium (conductive or non-conductive).
- Project Partner Results - The project partner results category consists of data that will only be provided to project collaborators and will not be publicly available. This category includes more detailed, anonymized results, as well as results from off-nominal

temperature, grid dynamics, and smart charge management control conditions. Shared data labeling is altered only to remove proprietary and business-sensitive information, and all project partners will be able to review data prior to its inclusion in the project partner results category.

- Proprietary Results - The proprietary results category consists of test results which contain proprietary and/or business-sensitive information, and which are provided only to the participating provider or manufacturer of the hardware under test. These results include many of the project partner results, but with the specific hardware system identified. Additional calculated metrics are provided as appropriate: time-aligned data and complete steady-state data sets are provided to the participating provider or manufacturer of the tested hardware upon request.

3.5 Procedures Development & Industry Feedback

The three distinct test categories or pillars were developed to characterize and capture profiles for EVs, EVSEs and fleet utilization. Detailed test procedures and processes were developed in collaboration with participating industry partners to ensure uniformity and accuracy across multiple testing entities.

Industry guidance from OEMs was provided to optimally pre-heat or pre-cool EV traction batteries prior to administering tests. Extra precautions to ensure test accuracy were additionally taken, such as securing all driver-controlled vehicle loads, ensuring simultaneous charging sessions were prohibited while NGP test data collection was in progress and delaying install of EVSE firmware updates to ensure consistency across all test data collected. Over-The-Air vehicle firmware and software updates were noted in specific test documentation.

4 Project Pillars

4.1 Electric Vehicle Profile Capture

Two types of EV profile capture testing were performed: nominal and off-nominal charge profile tests. EVs were charged from 10 to 100% SOC at nominal temperature conditions (23°C) with vehicle preconditioning, without any external charge management or limits imposed on the EVSE: These nominal test conditions were project-defined to compare performance under ideal and typical testing conditions across all EVs. Such values are denoted as nominal in the Type column of Table 1.

To cover the various test conditions across the parameters of interest, off-nominal conditions were explored for SOC, ambient temperature, and battery condition. Each test parameter is sampled sufficiently to gain information across its full range spectrum and appropriate tolerances are set accordingly. To better understand system response to external smart charging commands, charge management testing was included within off-nominal test conditions, where OCPP v1.6j smart charging commands were issued to curtail current to 65A for a 2-minute interval during the charge session. EVSE limited test cases were also included as an off-nominal condition, with both SCM and EVSE limited tests being performed under nominal SOC, battery temperature, and vehicle conditions. EV Charge profiles were captured for several combinations of the test conditions in Table 1 resulting in an extensive dataset.

Table 1 - EV Unmanaged Charge Profile Boundary Conditions

Test condition	Value	Tolerance	Type
Starting State of Charge (Display SOC)	10%	+/-2%	Nominal
	25%	+/-2%	Off-Nominal
	50%	+/-2%	Off-Nominal
Starting Battery Temperature	Cold – (-)7C	+/-2C *	Off-Nominal
	Nominal – 23C	+/-2C	Nominal
	Hot – 40C	+/-2C *	Off-Nominal
Starting Vehicle Condition	Soak	Steady State *	Nominal
	Pre-driven	Steady State *	Off-Nominal
Smart Charge Management	TxProfile, 2-minutes, 65A Limit	N/A	Off-Nominal
EVSE Limited	Secondary EVSE Power Cabinet Deenergized	N/A	Off-Nominal

* Some test condition variability may be present in select tests due to test location and weather limitations.

Vehicles evaluated in the NextGen Profiles project have characteristics summarized in Table 2:

Table 2 – NextGen Profiles captured EV Charging Profiles

EV	Model Year	Class	Battery Topology
EV1	2022	Light Duty	>500VDC
EV2	2021	Light Duty	>500VDC
EV3	2019	Light Duty	<500VDC
EV4	2023	Light Duty	<500VDC
EV5	2021	Light Duty	<500VDC
EV6	2022	Light Duty	<500VDC
EV7	2021	Light Duty	<500VDC
EV8	2022	Light Duty	>500VDC
EV9	2022	Light Duty	<500VDC
EV10	2022	Light Duty	<500VDC
EV11	2023	Light Duty	>500VDC
EV12	2019	Heavy Duty	>500VDC
EV13	2021	Heavy Duty	>500VDC

4.2 EVSE Characterization

EVSE characterization testing captured EVSE performance under varying conditions of ambient temperature, grid AC voltage characteristics and vehicle loading at various DC voltages and DC currents. Two types of EVSE characterization testing were performed: nominal and off-nominal power characterization tests. OCPP smart charge management response testing also provides insight into EVSE charge curtailment behavior.

4.2.1 Power Transfer Characterization at Nominal Conditions

Testing in a quasi-steady state is performed over an extensive array of DC voltage and DC current test points as shown in Table 3. Data is gathered for at least 5 seconds before connecting, before starting a charging cycle, after connecting, and upon concluding the charging session. Each steady state power transfer test point is captured for a minimum of 180 seconds to ensure the EVSE achieves quasi-stable operation.

Table 3 - EVSE Power Transfer Characterization Test Conditions

Test type	Test condition Category	DC Current Test Conditions	DC Voltage Test Conditions	Tolerance
Nominal	Steady State power transfer	50A to 500A in 10A increments (up to max power)	300V, 400V, 650V, 750V, 850V	+/-2%
Off-Nominal	Steady State power transfer	150A, 500A (or full power if 500A is not possible)	400V, 850V	+/-2%

4.2.2 Power Transfer Characterization at Off-Nominal Conditions

Testing is conducted at off-nominal boundary conditions across a reduced number of DC current and DC voltage test points to quantify the impact of ambient temperature, grid voltage, grid frequency, grid harmonic distortions and WPT alignment on the performance of advanced high-power charging infrastructure.

4.2.3 EVSE Grid Disturbance

Table 3 details the boundary conditions for varying grid parameters and ambient temperature as well as the off-nominal test cases for DC current and voltage test points.

4.2.3.1 Grid voltage variation

Voltage variation tests were conducted as described in SAE J2894-2-2015, which varies the voltage in 2% increments between 90% and 110% of the nominal AC input voltage.

4.2.3.2 Grid frequency variation

Frequency deviation testing was conducted in 1% steps between 98% and 102% of the nominal AC input frequency.

4.2.3.3 Grid Total Harmonic Distortion

Voltage harmonic distortion testing was conducted by starting with the nominal AC input and subsequently generating a distorted voltage waveform with 5% total harmonic distortion as described in SAE J2894-2-2015 and IEEE 519-2022.

Table 4 - EVSE Characterization Boundary Conditions

Test condition	Value	Tolerance
Grid Voltage	Nominal – 480VAC	+/-25VAC
	Swelled – 528VAC	+/-25VAC
	Sagged – 432VAC	+/-25VAC
Grid Harmonics	No harmonics	
	5% Voltage distortion	+/-1%
Grid Frequency	Nominal – 60 Hz	+/-0.2Hz
	Increased – 61.2 Hz	+/-0.2Hz
	Decreased – 58.8 Hz	+/-0.2Hz
Ambient temperature	Cold – (-)7C	+/-2C
	Nominal – 23C	+/-2C
	Hot – 40C	+/-2C *
* Some test condition variability may be present in select tests due to test location and weather limitations.		

4.2.4 Thermal Control System Testing

To determine the response and attributes of the thermal control system, multiple back-to-back charge sessions were conducted at high current with a representative rest time between charge events. Three consecutive 10-minute-long charge sessions were conducted at a test voltage of 750V and at the highest current possible with a maximum of 5-minute interval between charging sessions.

4.2.5 WPT misalignment tests

Quasi-steady state operation of the WPT system was conducted at the off-nominal conditions detailed in Table 5 for X, Y misalignment and Z-gap variation.

Table 5 - WPT Misalignment Boundary Conditions

Test parameter	Condition Metric	Tolerance	Test Type
X-Direction	Aligned (<5% coil length offset)		Nominal
	10% coil length offset	+/-2%	Off-nominal
	25% coil length offset	+/-2%	Off-nominal
	40% coil length offset	+/-2%	Off-nominal
Y-Direction	Aligned (<5% coil length offset)		Nominal
	10% coil length offset	+/-2%	Off-nominal
	25% coil length offset	+/-2%	Off-nominal
	40% coil length offset	+/-2%	Off-nominal
Z-Direction	Unloaded	+/-50mm from nominal airgap	Nominal

EVSEs evaluated in the NextGen Profiles project have characteristics summarized in Table 6:

Table 6 – NextGen Profiles EVSEs Charging Performance Characterized

EVSE	TEST ENVIRONMENT	CLASS
EVSE1	Laboratory	350KW
EVSE2	Laboratory	350KW
EVSE3	Field	250KW
EVSE4	Field	450KW
EVSE5	Field	250KW
EVSE6	Laboratory	125KW
EVSE7	Laboratory	100KW
EVSE8	Laboratory	270KW

4.3 Fleet Utilization Analysis

As fleet adoption of EVs and EVSEs increase, so does the need to improve understanding of EV and EVSE equipment capabilities, limitations, and behavioral utilization. While cursory familiarity with equipment capabilities can be obtained directly from the equipment specifications and practice with using the equipment, optimal employment requires a richer analysis that must examine the behavioral utilization of the equipment through case studies of existing EV and EVSE fleets.

Fleet utilization analysis was conducted for the NextGen Profiles project by installing external sensors and utilizing onboard telematics to collect data from vehicles and EVSEs operated by four different electrified public fleets over a two-year period. A high-level analysis of each individual fleet is performed using available data to understand fleets employment, charging utilization and explore mitigations that have the potential to lower costs and barriers to fleet electrification. Metrics used to gain insights into EV and Electric Vehicle Supply Equipment (EVSE) fleet utilization include hourly and daily power and energy demand, vehicle SOC at charge session initiation and completion and EV and EVSE temporal employment. Differences in employment needs, electrified fleet operational roles and market structures dictate individual (not collective) fleet evaluation to accurately characterize electrified utilization. Understanding EV fleet equipment, operations, utilization and behaviors will improve utilization and expand electrification of EV fleets to the existing fleet market.

EV and EVSE fleets evaluated in the NextGen Profiles project have characteristics summarized in Table 7:

Table 7 – NextGen Profiles Fleet Performance Analyzed

FLEET	MEASUREMENT LOCATION	NUMER OF EVs	NUMBER OF EVSEs
FLEET1	EV	23	10
FLEET2	EVSE	11	5
FLEET3	EVSE	8	8
FLEET4	EVSE	12	4

5 Project High-Level Takeaways & Results

The NextGen Profiles project was intended to investigate a representative sample of EVs and EVSEs capable of high-power DC Level 2 charging. Evaluating production EV charging performance, the characterization of EVSE equipment, and studying utilization of EV and EVSE fleets provided critical insight working towards this projects goal.

EV profile capture was performed across 13 electric vehicle assets. Under nominal defined starting conditions most EVs can achieve OEM rated peak power and charge times. Performance metrics were compared across EVs under these nominal conditions, highlighting that different EVs achieve different goals better than others. Performance metrics examined were peak power, average power, 10-80% SOC charge time, 10-100% SOC charge time, range gained, energy gained, thermal management, C rating, ramp rates, SCM response, EVSE limitation response, and adapter or boost converter limited response, among others. Off-nominal or boundary starting conditions of battery SOC, temperature, and pack conditioning resulted in some EVs exhibiting high degree of variance from nominal test conditions while other EVs demonstrated much more consistent charging performance across operating conditions. Future battery technologies were explored and compared to a top performing production EV in the NGP portfolio. Two-page portfolios were created for all thirteen EVs under test to further detail performance and data gathered through the NGP efforts.

EVSE performance characterization was performed on one 350 kW-capable conductive EVSE and one proprietary 100KW polyphase wireless charger and was by holding simulated vehicle traction battery voltage constant and sweeping the range of equipment-available charging current. Conductive EVSE testing was performed across a wide range of expected vehicle traction battery voltages for nominal defined starting conditions and then repeated for off-nominal or boundary starting conditions where AC grid voltage, frequency and harmonics were varied and SCM response was quantified. A high utilization characterization test was also performed. Wireless EVSE testing was performed under nominal defined starting conditions and then compared with a different set of WPT-specific off-nominal boundary conditions pertaining to misalignment and airgap scenarios between the EVSE and EV emulator coils. Conductive charging performance was evaluated across metrics including AC-DC efficiency, power quality, power loss, maximum available power, SCM curtailment latency and ramp rate, among others. Wireless charging performance was evaluated across metrics including DC output power in perfectly aligned condition at nominal airgap, operating frequency, efficiency at or near nominal power, input power factor and AC input voltage, among others.

Fleet utilization analysis was performed on four fleets of EV and EVSE deployments, comprising 54 EVs and 27 EVSEs over a two-year period. A high-level analysis of each individual fleet case study is performed using available data to understand fleets employment, charging utilization and explore mitigations that have the potential to lower costs and barriers to fleet electrification. Metrics used to gain insights into EV and Electric Vehicle Supply Equipment (EVSE) fleet utilization include hourly and daily power and energy demand, vehicle SOC at charge session initiation and completion and EV and EVSE temporal employment. Differences in employment needs, electrified fleet operational roles and market structures dictate individual (not collective) fleet evaluation to accurately characterize electrified utilization with the ultimate goals of lowering ownership costs and minimizing associated grid impacts and expanding electrification of EV fleets to the existing fleet market.

6 Project Failures & Deficiencies

Over the course of conducting NextGen Profiles project activities, some unexpected Device Under Test behaviors were observed and noted:

- One particular EVSE model, when configured in a specific configuration, was observed to draw large amounts of reactive power (approximately 150 times more reactive power than real power demand) when idle. This issue was documented and fed back to the manufacturer, who issued a firmware update that reduced unit idle power demand to reasonable and expected levels.
- One particular EVSE model was observed to have significant dips in power demand when the EVSE shifted load balance between its primary and secondary power towers. At scale, these types of power demand transients would have deleterious effects on the operation of the power grid.
- Multiple EVSEs evaluated for NextGen Profiles project testing only partially implement the Open Charge Alliance's OCPP protocol for version 1.6j. It was also observed that different OEMS implement portions of the standard differently.
- One particular EVSE reboots the EVSE kiosk every four hours when a internet connection to the OEM server is not established. This behavior presents a potential safety concern; the laboratory team observed a kiosk reboot in the middle of a test charge session without terminating the charge.
- One particular EVSE model was found to potentially overcharge a vehicle traction battery by relying on the vehicle to send a stop charge command.
- One particular EVSE was found to have incredibly noisy CCS connector and cable temperature instrumentation with indicated 80ºC swings in temperature. Noise on the CCS connector and cable temperature lines was found to inhibit the maximum charging speed of the EVSE until a software update was applied.
- One particular EV model's default charging behavior was observed to charge to 90% SOC. The default behavior could be overridden with manual user input before every charge session.
- One particular EV model exhibited a maximum charging power that exceeded the OEM's stated value by approximately 7%.
- One particular EV with 800VDC battery pack topology was found to have a power limit that was 45% lower when paired with a particular 500VDC EVSE than when paired with other 500VDC-capable EVSEs.
- One particular EV-EVSE combination had a first-time plug-in success rate below 33%.

7 Project Future Research & Planning

Future NextGen Profiles project areas of study will include:

- Review and revise test plans and procedures document and solicit industry review, feedback and input
- Continue EV profile capture activities; expand set of profiled EVs
- Continue EVSE performance characterization activities; expand set of characterized EVSEs
- Capture charging profiles of EV boost converters for EVs with 800VDC pack topologies
- Characterize performance impact of charging adapters
- Characterize performance of MCS systems
- Characterize performance of V2X-capable systems

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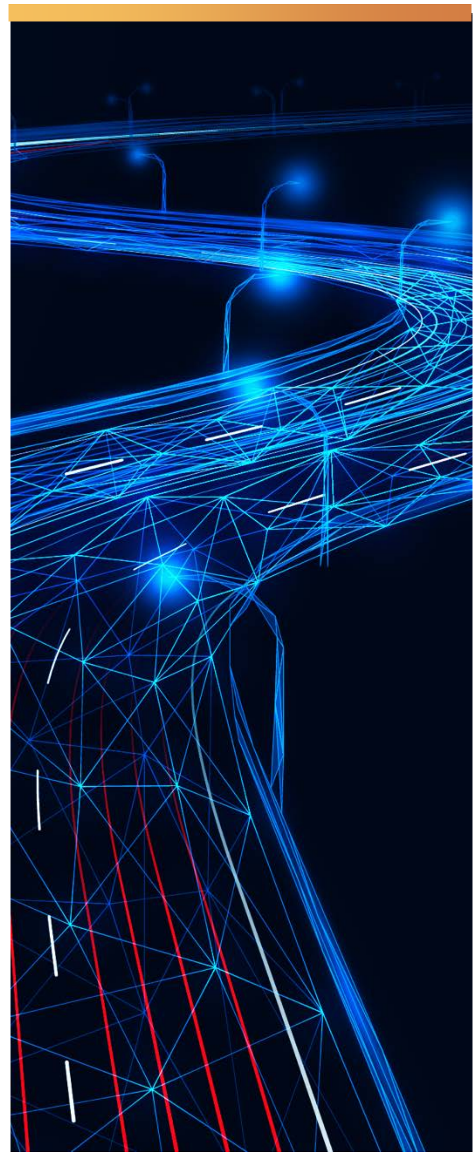

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