EVs@Scale: Next-Gen Profiles

EV Profile Capture 2024

ANL/TAPS-25/2

Argonne NATIONAL LABORATORY

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List of Acronyms

NGP	Next-Gen Profiles
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
ICE	Internal Combustion Engine
DC	Direct Current
AC	Alternating Current
OEM	Original Equipment Manufacturer
LD	Light-Duty
HD	Heavy-Duty
BMS	Battery Management System
CCS	Combined Charging System
CAN	Controller-Area Network
OBD	On-Board Diagnostics
UDS	Unified Diagnostic Services
OCPP	Open Charge Point Protocol
DAQ	Data Acquisition System
HPC	High Power Charging
SOC	State of Charge
SCM	Smart Charge Management
XCEL	eXtreme fast charge Cell Evaluation of Lithium-ion Batteries
XFC	eXtreme Fast Charging
DOE	U.S. Department of Energy

Executive Summary

As part of the U.S. DOE EVs@Scale consortium *Next-Gen Profiles (NGP)* project, the profile capture and analysis of production electric vehicles undergoing high power charging (HPC) is conducted over a wide range of conditions to explore variance and performance. Charge session parameters are collected from both the electric vehicle (EV) and electric vehicle supply equipment (EVSE) at a rate of 10Hz and entered into a time-series database for analysis. These charge profiles are captured under nominal and off-nominal conditions, exploring the impact of battery state of charge (SOC), battery temperature, vehicle condition, smart charge management (SCM), and EVSE limitations. Nominal conditions are defined to be ideal conditions that should transfer the maximum allowable energy in the minimum possible amount of time. Nominal condition profiles are compared across EVs to characterize state-of-the-art EV charging performance against one another. Off-nominal condition profiles are compared against its nominal condition profile counterpart to highlight the variance across less desirable starting conditions within a single EV.

This *EV Profile Capture 2024* report stands as an update from the *EV Profile Capture 2023* report to include the additional EV & EVSE assets tested and analyzed in 2024. The major updates within this report include the addition of three next-generation electric vehicles, added test cases, and further analysis. This expansion of analysis includes power profiles, power distribution, quantifying SOC, energy and range performance, EVSE limitation impacts, boost converter performance, etc. Additionally, NGP time-series data has been used as input towards three national laboratory-led grid modelling efforts: ANL's IEEE-37 HIL model, INL's Caldera model, and NREL's EVI-X model. A summary of these platforms and how NGP has worked to improve their effectiveness has also been added to this years' report.

Under nominal conditions, most EVs can achieve the original equipment manufacturer (OEM) rated peak-power and charge times. Peak power across EVs has variance due to the vehicle design, battery topology, charging strategy, etc. These 10-100% nominal preconditioned charge profiles across 16 EVs (14 light-duty (LD), 2 heavy-duty (HD)) were used for analysis in power curve analysis, power distribution, SOC and range comparison, thermal impacts of current draw, battery pack size and energy charged, and ramp rates.

Power curve analysis show the uniqueness in power vs time curves across all EVs, breaking down the features of a typical profile and where variation is typically seen. Power distribution results showed that over 50% of charge time is spent below 50kW and only 12.1% is spent above 200kW. SOC and range performance yielded different top performing EVs when exploring goals of performance from SOC and range gained after 10-min (EV2) and 20-min (EV8), and time-to-achieve 80% SOC (EV8) and 200 miles of range (EV1). Current draw from 400-volt EVs had a higher thermal impact to cable/connector temperatures when compared to 800-volt EVs, due to a higher current requirement to achieve similar power levels. There was high variance in C rating, a useful metric when comparing the relationship between peak/average charge session power and

relative battery pack size, across EVs under test. Ramp rates during initial power transfer were examined, fastest and slowest speeds ranging from 192.5kW/second to 2.6kW/second respectively. A similar analysis of ramp rates was also conducted for OCPP curtailment testing, where EVs underwent a 2-minute 65A curtailment request before returning to full-power charge.

Under off-nominal conditions, most EVs experienced variation from the nominal condition profiles. EVs that underwent the full set of NGP defined testing conditions were compared, analysis of which was categorized by 800-volt and 400-volt EVs. It should be noted that the 800-volt EVs had significantly higher peak power ratings than the 400-volt EVs, and thus were more prone to variance. Initial state of charge, battery temperature, and vehicle condition had a considerable impact on peak power levels and charge time for the 800-volt vehicles under test. EVSE limited tests lowered achievable power down to 150kW, greatly impacted 800-volt charging power, and had little to no effect on 400-volt charging power. Adapter testing was performed on a single 400-volt EV, where power and current limitations were found but overall charge time was not significantly impacted. Adapter and boost converter testing was performed on a single 800-volt EV, where both charge power and charge time were greatly impacted.

ANL’s IEEE-37 HIL grid model, INL’s Caldera modelling platform, and NREL’s EVI-X modelling platform all made the effort to integrate NGP EV profile capture data this year. Each platform did so to increase the accuracy and effectiveness of their models, using real-world charging data rather than simulated profiles. This report delves deeper into what the goals of these models were and how specifically NGP data was used to improve them.

Charge profiles are unique, and comparing such requires analysis that examines starting conditions, vehicle and battery topologies, charger capabilities, etc. Examining performance under one charging performance metric alone is not sufficient, and requires power, SOC, range, energy, ramp rates, temperature, etc. to all be considered. This full range of analysis is especially important for grid operators, current/future EV owners, and researchers if looking to capture the current state of DC fast charging on production electric vehicles. The NGP research captures such data with high fidelity and looks to increase its portfolio and analysis in future reports.

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1 Electric Vehicle Profile Capture Introduction

This report provides data and results from the electric vehicle (EV) profile capture results conducted for the U.S. DOE EVs@Scale Next-Gen Profiles (NGP) project. The analysis within this report is a continuation of effort that was captured within a series of four reports published in 2023; EV Profile Capture 2023, EVSE Characterization 2023, Fleet Utilization 2023, and High-Level Analysis and Procedures 2023. This *EV Profile Capture 2024* update report will be released alongside two others; *EVSE Characterization 2024*, and *Fleet Utilization 2024*.

The test article nomenclature in these reports was aligned for cross report comparison. For example, EV1_22_LD_>500V refers to EV#1, a model-year 2022 light-duty vehicle with battery voltage topology above 500-volts. EVSE2_H1 refers to EVSE#2 operating on the CCS-1 liquid-cooled cable, the first of two charge dispenser cables. This nomenclature was chosen for EV and electric vehicle supply equipment (EVSE) anonymization to contain enough relevant information for comparison without identification.

1.1 EV Profile Capture Significance Within NGP

This report studies the impact of initial vehicle conditions over the course of a charge session. Several factors influence an electric vehicle's charging profile during a full-charge event; the most impactful of which are the starting state of charge (SOC) and initial battery temperature. Currently, the public has a general understanding of ideal charging characteristics and profiles for many HPC EVs. However, there is little public knowledge about how charging characteristics change around varied boundary conditions. These boundary, or "off-nominal" conditions, are initial conditions of the vehicle and charger that may impact charging performance. Understanding how changes in boundary conditions affect charging profiles allows consumers to become knowledgeable and informed about the market and charging capabilities of electric vehicles. In tandem with boundary conditions, vehicle battery topology considerations are of particular interest, specifically 400-volt and 800-volt systems. These EV battery topologies influence charging performance in several ways and are explored in depth within this paper.

The work presented sets out to characterize 16 vehicles across 20 sets of boundary conditions and 4 types of EVSEs. Of these 260 different profile possibilities, 175 were able to be captured. Highlighted are 138 profiles, with three different initial SOC conditions, three battery temperature conditions, two vehicle conditions, one charge management case, and two EVSE limited conditions.

1.2 What Are EV Charge Profiles

EV charge profiles are shaped by the charging capabilities, limitations, and management of the vehicles' internal battery when conducting a charge session. For the interest of a consumer, the charge profile capability is related in terms of the state of charge and range, much like an internal combustion engine (ICE) vehicle would indicate the liquid level in the fuel tank. The amount of time required to achieve SOC and range milestones aid drivers in minimizing time spent at DC fast charging stations. For the interest of original equipment manufacturers (OEMs), grid providers, and researchers, power is often the metric used for performance comparison. Typically, power is the determining factor when it comes to component sizing, grid planning, cost analysis, charging speeds, etc. and must be understood when improving, managing, and categorizing EV charging strategies.

1.3 What Influences EV Charge Profiles

Employing high level communication protocols, electric vehicles transmit a wide range of information to direct current (DC) EVSE. This information includes details such as limits, state of charge, and requested current. This exchange of information guides the EVSE to provide the necessary requested current to the vehicles upon request, within the constraints set by the EVSE for the charging session. The request for DC current is regulated by the vehicle's Battery Management System (BMS), whose charge profile is programmed by vehicle Original Equipment Manufacturers (OEMs). The executed profile considers factors such as SOC and temperature. The BMS of an electric vehicle is designed to oversee the battery's requirements during charging and usage, ensure safety threshold integrity, and manage the longevity of the traction battery's lifespan. Numerous specifics related to these BMSs, and charge profiles are deemed proprietary information protected by vehicle OEMs.

1.4 Value behind EV Charge Profiles

A healthy and equitable EV charging market requires improved OEM, energy utility provider and consumer understanding of EV charging profiles. Understanding the possibilities, limitations, and the exact influences that an EV experiences while charging will help maximize the value of actively managing EV charging energy demand and can influence consumer EV purchasing behavior.

2 EV Profile Capture Measurements

Approximately 25 parameters were collected to quantify and characterize the EV and EVSE charging system while in operation. The following sections define the measurement parameters, locations and data collection equipment used for each EV charge session.

2.1 Measurement Parameters

The electrical measurement accuracy requirement for both the AC and DC measurements was ± 0.1% of reading PLUS ± 0.1% of full scale. The temperature measurement accuracy requirement was ± 0.1°C. All measurement parameters were sampled with a cadence of 10 Hz, except for equipment metadata.

2.1.1 EVSE Measurement Parameters

The full list of EVSE measurement parameters can be seen in Table 1: EVSE Measurement . It should be noted that many of the same measurement parameters are similarly described in the *EVSE Characterization: A Next-Gen Profiles Project Report* document. EV emulators were not employed for EV profile capture, and as of such, characterization of the liquid cooled Combined Charging System (CCS) cable and connector was not considered in this report.

Table 1: EVSE Measurement parameters

EVSE Measurement Type	Parameter	Phase	Units
EVSE Meta-data	EVSE Unique ID	-	-
	EVSE Firmware / Software Version	-	-
	Timestamp	-	MM/DD/YY hh/mm/ss.dd
480VAC Input to Each Power Cabinet	Voltage	A, B, C	V (RMS)
	Current	A, B, C	A (RMS)
	Frequency	A, B, C	Hz
	Real Power	A, B, C	W (RMS)
	Reactive Power	A, B, C	VAR (RMS)
	Apparent Power	A, B, C	VA (RMS)
	Power Factor	A, B, C	%
	Current THD	A, B, C	%
	Current Harmonics	3^{rd}, 5^{th}, 7^{th}, 9^{th}	% (of Ideal)
Energy Management Source	OCPP Server / E-mobility Service Provider, Other	-	Curtailment Request (A or kW)
EVSE Charge Pedestal (Dispenser) Output	Voltage	DC	V
	Current	DC	A
	Power	DC	W
	Energy Charged	DC	Wh
	Dispenser Supply Fluid Temp	-	°C
	Dispenser Return Fluid Temp	-	°C
EVSE Auxiliary System(s)	Voltage	AC	V (RMS)
	Current	AC	A (RMS)
	Power	AC	W (RMS)
	CCS Cable Temperature	-	°C
EVSE CCS Cable	CCS Connector Temperature	-	°C
EVSE CCS Connector	Cabinet 1 Internal Air Temperature	-	°C
EVSE Power Cabinet	Cabinet 2 Internal Air Temperature	-	°C

The EVSE Unique ID, Firmware, and Software version parameters have been omitted, or altered, for anonymity. The Energy Management Source Curtailment Request was only recorded for sessions that were performed with Smart Charge Management testing. For some tests, EVSE measurements were not able to be obtained, or were extremely limited due to alternative EVSE configurations and testing through off-site, public charging equipment.

2.1.2 EV Measurement Parameters

This section details the EV measurement metrics that were observed/collected at a sample rate of 10Hz when conducting EV charge sessions. All the EV measurement parameters are shown in Table 2: EV measurement parameters.

Table 2: EV measurement parameters

EV Measurement Type	Parameter	Phase	Unit
EV Meta-Data	EV Unique ID	-	-
	EV Firmware / Software Version	-	-
	Timestamp	-	DD/MM/YYYY hh:mm:ss.000
	Vehicle Traction Battery Nominal Voltage	DC	V
	Vehicle Traction Battery Nominal Capacity	DC	kWh
CAN-Bus	Display Battery SOC	-	%
	Actual Battery SOC	-	%
	Average Battery Temperature	-	°C
	Minimum Battery Temperature	-	°C
	Maximum Battery Temperature	-	°C
	Battery Voltage	DC	V
	Battery Current	DC	A
	Battery Power	DC	W
	12V Battery Voltage	DC	V
	Range	-	miles
	Ambient Temperature	-	°C

For this report, some of the EV Meta Data parameters have been omitted, or altered, for anonymity. All measurement parameters were included for each captured charge session. The "Display Battery SOC" was used to define the "Initial State of Charge" boundary condition. The "Average Battery Temperature" was used to define the "Battery Temperature" boundary condition.

2.2 Measurement Locations

2.2.1 EVSE Measurement Locations

This section details the locations of the measurements taken for each parameter described within 2.1.1 above. This section is also described in more detail in the *EVSE Characterization: A Next-Gen Profiles Project Report* document.

To produce consistent measurements across multiple charger topologies, the measurement locations for each topology being tested needs to be explicitly defined. Figure 1 depicts the two types of charger topologies, paralleled at the dispenser, and paralleled at the primary power cabinet, used for testing the charging characteristics of EVs in this report. On the left of the figure, each power cabinet is DC coupled directly to the EVSE dispenser; this is considered a paralleled system coupled at the dispenser. On the right image of the figure, the power cabinets are coupled to each other and only have a single DC connection to the dispenser; this is considered a paralleled system that is coupled at the primary cabinet. This difference of topology drives requirements on the measurement locations for each system to properly characterize the power flow within the charging system.

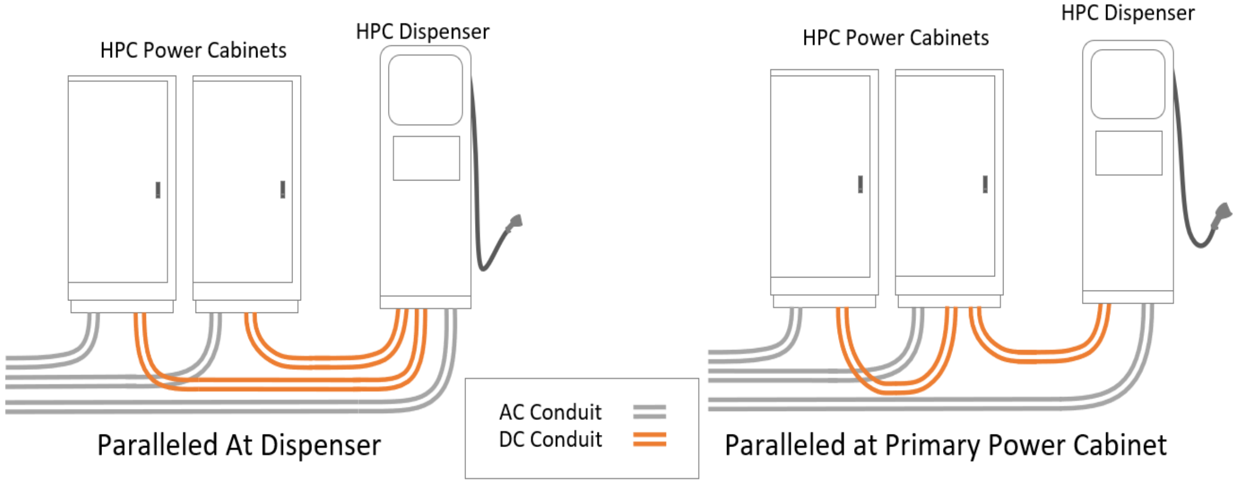


Figure 1: EVSE System Topologies

As depicted in Figure 2Figure 1, the alternating current (AC) electrical input to the HPC EVSE was measured at the input to each power cabinet as supplied from (downstream of) the local service panel. For three phase measurements, the two-wattmeter method was employed for some of the charge sessions and direct measurements of all three phases were also used. The DC output from the EVSE was measured at the dispenser input during all testing for the EV charging characterization tests. If the EVSE topology included an additional DC-DC converter internal to the dispenser, the DC measurement point was at the final output of the additional DC-DC converter. This measurement point, at the input of the cable connection from the dispenser to the EV inlet, was not diagrammed.

The auxiliary system measurements in the HPC EVSE include but are not limited to cooling, controls, lighting, front touch panels, and other loads. These were measured at the source location in the EVSE. The DC output and the AC auxiliary power measurement locations at the dispenser are shown in Figure 3 for both EVSE topologies used in this project.

The temperature measurements obtained in this project were measured as close to the described locations as possible. Cable temperature was measured at the surface of the coolant system tubing in the cable. The Dispenser Supply and Returning Fluid Temperature were measured at the surface of the coolant system tubing, in both entry and exit points respectively. EVSE Power Cabinet Internal Air Temperature was obtained midway through the inside of the cabinets.

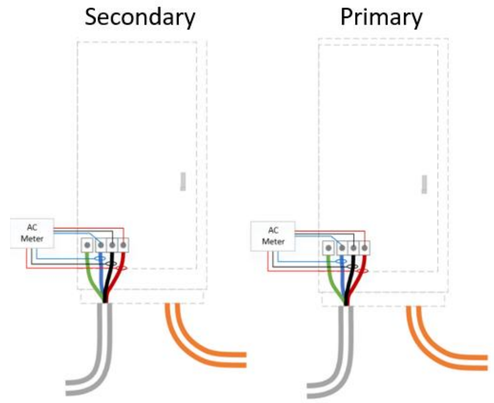


Figure 2: EVSE Secondary and Primary Power Cabinet 480VAC Metering

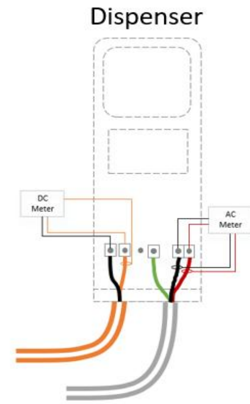


Figure 3: Charge Dispenser DC and AC Auxiliary Power Metering Locations

2.2.2 EV Measurement Locations

EV parameter measurements were made through the vehicle Controller Area Network Bus (CAN-bus) interface. Most vehicle data was read from the on-board diagnostics (OBD-II) port, which provided access to vehicle data through unified diagnostic services (UDS) protocol. In cases where the vehicle did not have an OBD-II port, high-speed CAN-bus data was accessed directly. Vehicle Meta-Data was obtained directly from the vendor when listed, but for the purpose of this report Meta-Data has been omitted or altered to keep vehicle information anonymized.

2.3 Measurement Equipment

2.3.1 EVSE Measurement Equipment

Equipment used for the measurements of the EVSE during an EV charge session included power analyzers, AC/DC current probes, voltage taps, and additional thermistors where necessary. These were utilized to obtain all the previously mentioned EVSE measurement time-series parameters. Equipment was chosen to meet all current and voltage requirements at a sampling rate that met the NGP defined frequency of 10Hz.

2.3.2 EV Measurement Equipment

Measurements of EV data during the charge session were made using the CAN-bus interface, which required telemetry devices to read, and log needed data. To access the CAN-bus using the OBD-II port, a CAN transceiver device was utilized. This device utilized UDS CAN protocol to request/receive data from the vehicle for charging specific information. To decode specific messages, vehicle scan tools were used for database creation on a vehicle-to-vehicle basis. This also was used to understand potential faults and error codes that might come about when charging.

3 EV Profile Capture Testing Conditions

EV profile capture testing was designed to characterize and quantify electric vehicle charging profiles without damaging them. EV charge profile capture testing aimed to quantify a large set of charging profiles for a representative sample of available electric vehicles that characterize the charging power profile of the vehicle and charger combination.

3.1 Nominal & Off-Nominal Conditions

This section highlights the EV and EVSE testing conditions when characterizing EVs during a charge session. Table 3 describes the EV testing condition parameters and Table 4 describes the EVSE testing condition parameters used when obtaining an EV charge profile; there exists a total of twenty possible EV charge profiles per EV. While not every EV was able to be characterized under all combinations of these conditions, all EVs were subject to profile captures under nominal test conditions.

A nominal test was conducted under ideal conditions that should transfer the maximum allowable energy in the minimum possible amount of time. The following EV parameters must have been fulfilled to complete a nominal test: "starting SOC" of the vehicle must have been 10%, "starting battery temperature" must have been 23°C, "starting vehicle condition" must have been preconditioned. For the EVSE, the following parameters must have been fulfilled to complete a nominal test; "Outside Ambient Temperature" must have been at 23°C, "Smart Charge" values all must have been FALSE, and no limits were placed on the EVSE cabinets or available DC current.

Table 3: EV condition parameter requirements

EV Condition Parameter	Parameter Requirement	Tolerance
Starting State of Charge	10% (Nominal)	± 2% (Reported Usable*)
	25%	± 2% (Reported Usable*)
	50%	± 2% (Reported Usable*)
Starting Battery Temperature	23°C (Nominal)	± 2°C
	40°C (Hot)	± 2°C
	-7°C (Cold)	± 2°C
Starting Vehicle Condition	Preconditioned	Variable**
	Soaked	Steady State***
Reported Usable* - SOC value was based on the reported available SOC to the user; not the absolute SOC of the battery pack.		
Variable** - Battery pack was pre-conditioned (heated or cooled) to a vehicle target temperature via drive cycle; preconditioning was performed once vehicle battery has reached target starting battery temp.		
Steady State*** - Vehicle was temperature soaked for a minimum of 4-hours under target weather conditions.		

Table 4: EVSE condition parameter requirements

EVSE Condition Categories		Condition Metric Requirement	Tolerance
Outside Ambient Temperature		23°C (Nominal)	± 2°C
		40°C (Hot)	± 2°C
		-7°C (Cold)	± 2°C
Smart Charge	Request	FALSE (Nominal)	–
		TxProfile	–
	Duration	No Limit (Nominal)	–
		2 Minutes	–
	Scheduling	No Request (Nominal)	–
		2 (min) After Charge Session Start	± 1 (min)
	Value	No Limit (Nominal)	-
		65A (AC Input Current)	-
EVSE Limited		No Limit, Dual Tower (Nominal)	–
		Limited, Single Tower	–
		Limited, 150kW	–
		Limited, 500V	–

Nominal starting battery temperature conditions were met by keeping the EV inside a temperature-controlled room for an extended period and confirming vehicle battery temperature data via the CAN-bus. Off-nominal battery temperature conditions were achieved by leaving the vehicle outside for an extended period on days meeting ambient weather requirements listed above in Table 3: EV condition parameter requirements.

To qualify as a Smart Charge or EVSE Limited test, the EV and EVSE must have been operating under nominal conditions for SOC, temperature, and vehicle conditioning. These tests characterized the EV charge profile with charging system current limitations.

3.2 On-site & Off-site Testing

Several EV charge sessions were conducted off-site in a non-laboratory setting. Field testing was performed under the same initial conditions to ensure consonant EV charge profiles were collected. Off-site testing had limitations in the amount of EVSE boundary conditions and amount of available EVSE telemetry. Because field and laboratory testing were not significantly different, they were not differentiated in this report.

4 EV Profile Capture Testing Results

This section elucidates the quantitative and qualitative outcomes discovered within the analysis of Next-Gen profiles, showcasing significant areas of interest in terms of the performance of DC fast charging. The data collected through rigorous testing procedures is presented and analyzed in detail, revealing key insights and observations pertinent to the research objectives.

4.1 Typical EV Charge Profile Anatomy

EV charge profiles have many unique characteristics across different EV implementations that are impact by starting conditions, EVSE power availability, battery degradation, etc. Performance of charge sessions are analyzed in many ways, one of which is by analyzing DC power, current, and voltage throughout the full duration of the charge. Figure 4 shows the typical charging behavior in Li-ion batteries (currently one of the most common EV battery chemistries implemented today), this example being a 5V battery. Relating that to an 800VDC EV charge profile collected in Next-Gen Profiles, the two share many similarities.

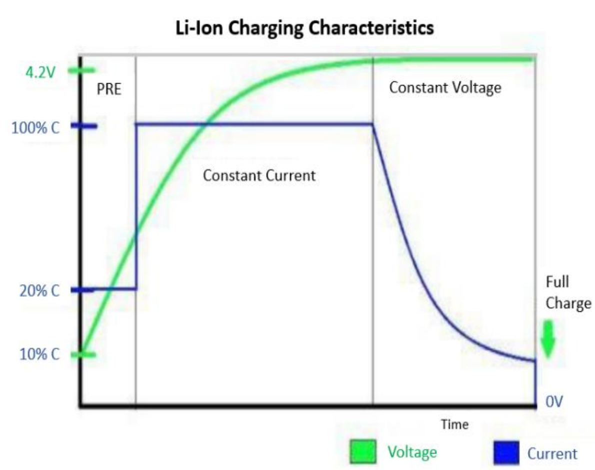


Figure 4: Typical Li-ion Battery Charging Curve (Source: Texas Instruments) [2]

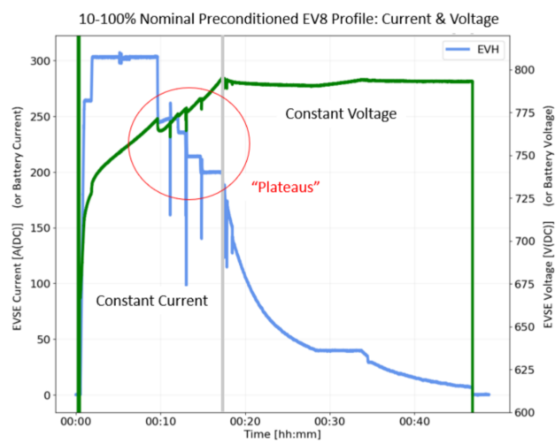


Figure 5: DCFC Session on Conventional EV (Source: Next-Gen Profiles)

This power profile (power vs. time, or current vs time plot) for electric vehicle DC fast charging typically starts with high power during the "constant current" phase of the charge and gradually decreases as the battery SOC and temperature increases. Power steps in this phase are often referred to as “power plateaus” where step changes are observed before reaching the “constant voltage” phase, which may occur for a number of reasons that are unique to the EV charging strategy, EV conditions and the capabilities of charging equipment under use.

As the state of charge increases the session transitions to a "constant voltage" phase, where power gradually decreases because the vehicle modulates requested current to prevent battery overvoltage. As the battery nears full capacity, power decreases significantly to prevent overcharging and tapers the charging process off until completion.

4.2 Comparing Performance

EV charging profiles of various electric vehicle models were evaluated by comparing time series power profiles, state of charge and range, energy charged, current draw, EV battery topologies, power C-rating, ramp rates and OCPP curtailment.

4.2.1 Time Series Power

Analyzing EV charging power profiles over time helps compare how vehicles charge over a given period, aids users to manage energy consumption, plan charging schedules effectively, and enables efficient and optimized charging experiences for both users and grid managers. Power profile curves for EV charging vary among different electric vehicles due to their battery capacities, BMS and powertrain design, charging technologies, initial conditions, and internal systems, resulting in distinct charging profiles. This uniqueness influences factors like charging speed, peak power demands, and the duration spent at various charging levels, reflecting the diverse characteristics and capabilities of each EV model.

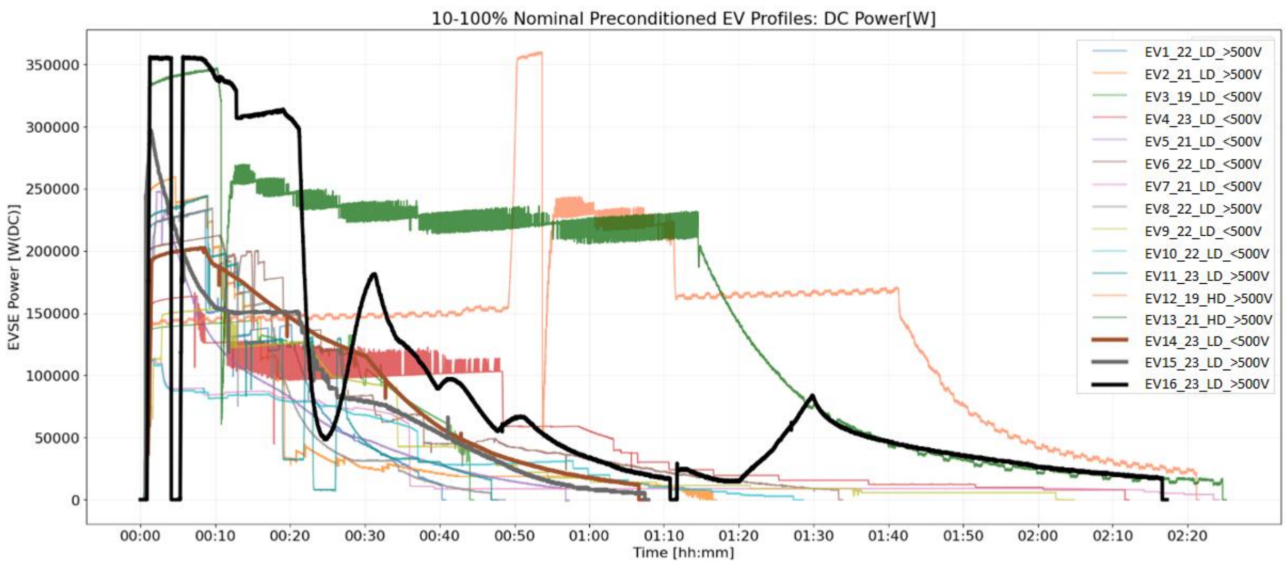


Figure 6: 10-100% Nominal Preconditioned: DC Power vs Time

Figure 6 includes the top performing charge sessions across the NGP portfolio of EVs under nominal starting conditions of 10% starting SOC, ≈23°C starting battery temperature, pre-driven on a 40-60minute drive cycle prior to charge, and charging until SOC is 100%. These results were intended to showcase the diversity and uniqueness in charge performance with relation to power over time. Power profiles for EV14, EV15, and EV16 have been highlighted as they are new additions to the NGP portfolio in 2024.

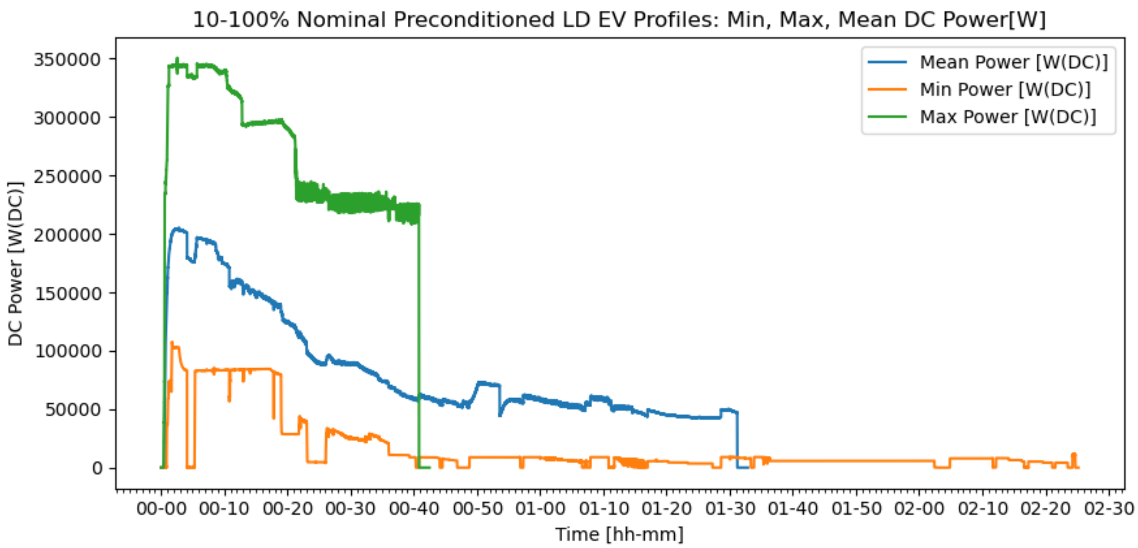


Figure 7: 10-100% Nominal Preconditioned LD EV Profiles: Min, Max, Mean DC Power

Figure 7 utilizes the charge profile data from Figure 6 to create hypothetical best performing (Max), worst performing (Min), and average charge performance (Mean) in terms of DC power and charge time from the 14 LD EVs under test. The Max profile was calculated using max DC power of all 14 LD profiles throughout the time-aligned charge sessions seen in Figure 6, with the profile curve terminating at the time from the shortest duration charge session. Conversely, the Min profile was calculated using the min DC power of all 14 LD profiles, terminating at the time from the longest duration charge session. Mean profile calculated using the average across all 14 profiles, and ended at the average of all charge session's duration.

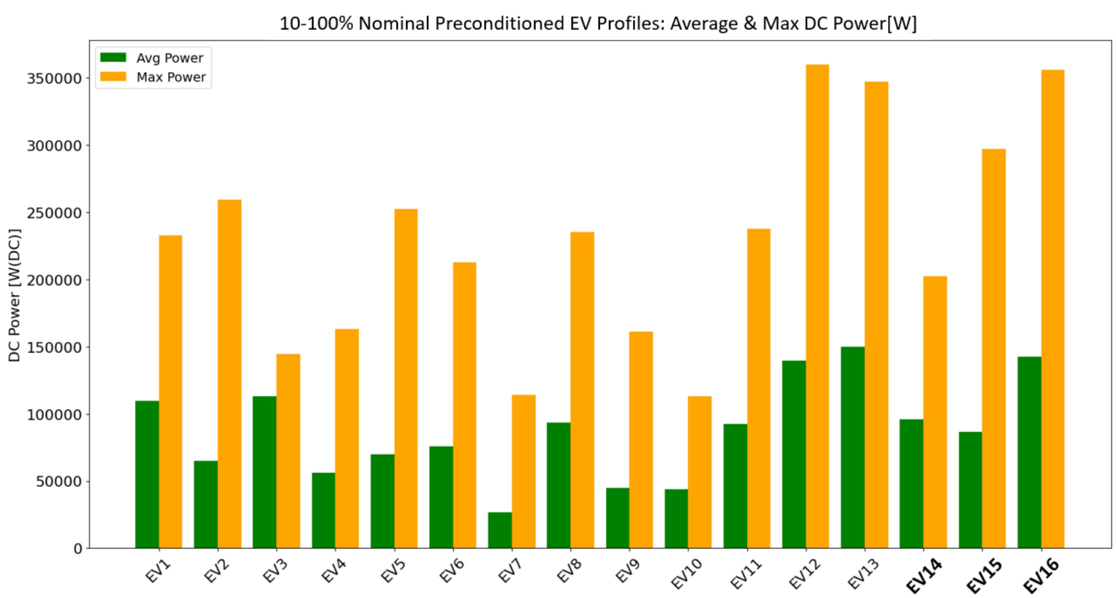


Figure 8: 10-100% Nominal Preconditioned: Average & Max DC Power

Figure 8 summarizes average and maximum power for each EV asset charging under nominal conditions from Figure 6. The relationship between peak and average power provides useful information about the implemented EV charging strategy. For example, EV3's peak power was much lower than EV2, however its average power was higher. This could be due to a more conservative charging experience with EV3, utilizing lower peaks for longer durations that can ultimately lead to shorter total charge time from 10-100% SOC. However, the approach of higher peaks for shorter duration seen by EV2 was a common strategy intended for a shorter charge time from 10-80%, utilizing high power in the early stages of the charge session and sacrificing performance during the later stages of charge. Both strategies were equally valid, having their own pros/cons that may benefit the EV driver in different ways. Grid operators must be able to accommodate the additional aggregate grid load from all types of DC fast charging strategies. Table 5 contains additional performance metrics on each of the power curves from Figure 6.

Table 5: 10-100% Nominal Preconditioned: Performance Details

EV	Class	Charging Battery Voltage [V(DC)]	Peak DC Power [kW]	Avg DC Power [kW]	Time Spent <100kW [min]	Time Spent 100-150kW [min]	Time Spent >150kW [min]	Total Charge Time [min]
EV1	LD	>500V	200-250	~105	18.7	10.6	10.5	39.8
EV2	LD	>500V	250-300	~65	58.1	3.5	14.3	75.9
EV3	LD	<500V	100-150	~110	13.5	30.0	0.0	43.5
EV4	LD	<500V	150-200	~55	87.0	37.2	6.9	131.1
EV5	LD	<500V	200-250	~70	42.7	7.5	6.1	56.3
EV6	LD	<500V	200-250	~75	66.5	8.4	18.0	92.9
EV7	LD	<500V	100-150	~25	140.6	2.4	0.0	143.0
EV8	LD	>500V	200-250	~95	28.1	1.9	16.4	46.4
EV9	LD	<500V	150-200	~45	97.0	17.3	7.6	121.9
EV10	LD	<500V	100-150	~45	84.5	2.3	0.0	86.8
EV11	LD	>500V	200-250	~95	26.4	7.0	13.0	46.4
EV12	HD	>500V	350-400	~130	34.9	45.1	60.7	140.7
EV13	HD	>500V	300-350	~145	59.6	6.7	77.9	144.2
EV14	LD	<500V	200-250	~95	35.0	13.3	17.7	66.0
EV15	LD	>500V	250-300	~90	43.1	3.7	20.0	66.8
EV16	LD	>500V	350-400	~140	102.2	8.2	23.4	133.8

In Figure 9 the evaluated power curves were segmented into 50kW buckets to visualize the amount of charge session time each EV spent within a range of power. Rather than comparing total charge time, this was analyzed using a percentage of total charge time for comparison. A high degree of variance was seen when examining these buckets on a vehicle-to-vehicle basis, however it was clear the evaluated EVs spent most of their charging at power levels <50kW. This analysis could further be separated into smaller/larger bucket sizes if desired.

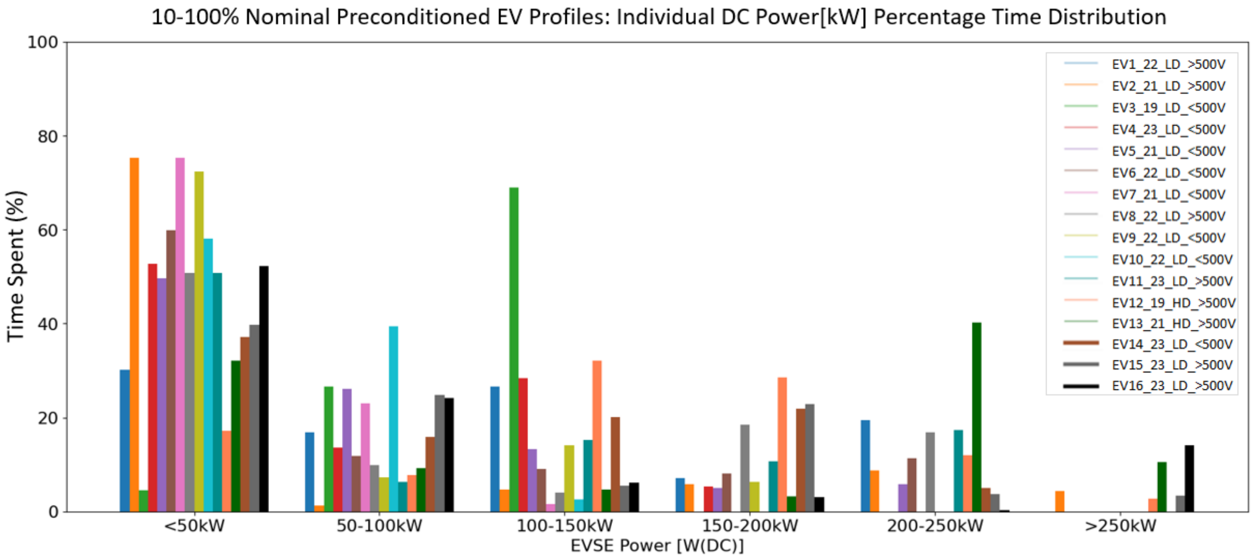


Figure 9: 10-100% Nominal Preconditioned: Individual DC Power Percentage Time Distribution

Combining the individual results from Figure 9, an aggregated power distribution of the sixteen NGP EVs was derived. Figure 10 gives a percentage breakdown of time spent within the specified 50kW regions, of which just under 50% was spent below 50kW and 14.7% was spent above 200kW.

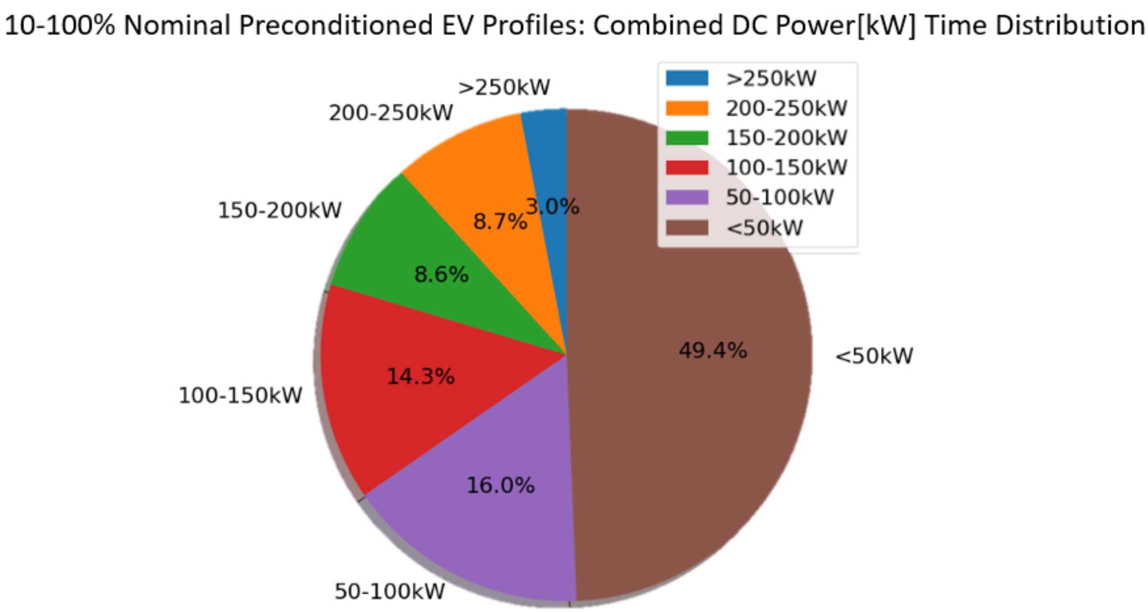


Figure 10: 10-100% Nominal Preconditioned: Combined Power Distribution

4.2.2 State of Charge, Range, Energy Charged

Understanding charge performance metrics like state of charge gained, range added, and energy charged is vital for EV drivers to make informed decisions regarding charging strategies, minimizing travel, charging time, and managing battery health. This information also assists prospective EV users by informing them of their choices when adopting electric vehicles and managing their charging needs.

Different goals or benchmarks are often used to characterize charge performance in terms of SOC, range, and energy charged. Figure 11 depicts charging performance as measured through SOC, energy, and range gained after 10 minutes and 20 minutes of DC charging, sorted using an SOC bias. EV8 was the highest performing when it comes to SOC gained after 20 minutes of charging, but EV2 was the highest performing for SOC gained after 10 minutes. The ranking of top performing EVs would further change if the metrics were changed to different end goals such at 5 minutes, 15 minutes, etc.

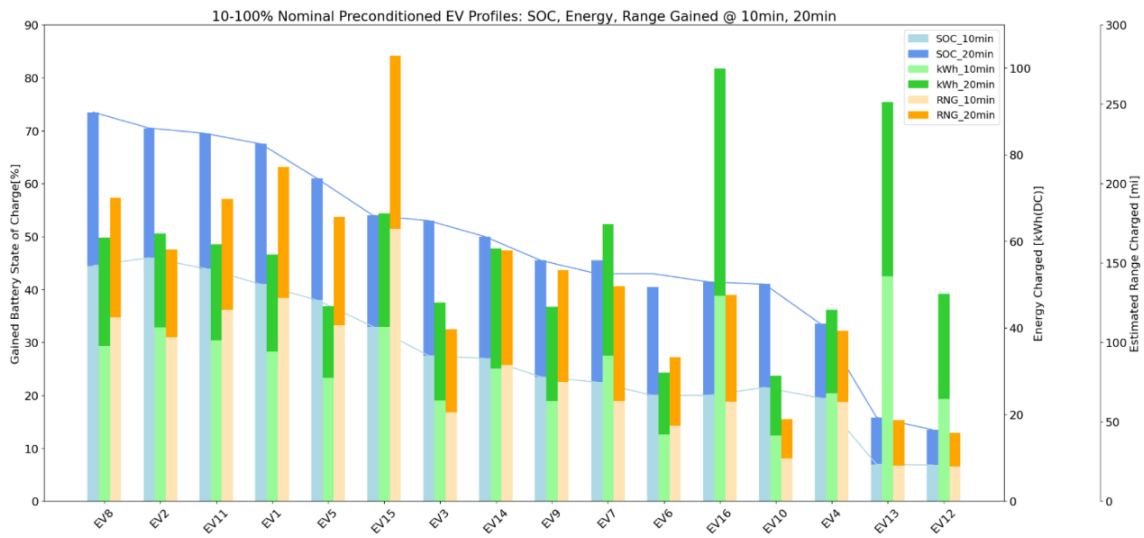


Figure 11: 10-100% Nominal Preconditioned: SOC, Energy, & Range After 10-min & 20-min – SOC Biased

The same comparison was done in Figure 12, except the performance metric sorting criteria was changed from SOC to energy charged (kWh). Here it was seen that EV8 falls from top performing EV down to sixth, being replaced with EV16 that was previously ranked in eleventh place in an SOC biased comparison. This new perspective shared insights on how much energy was being transferred into the EV battery pack, a useful metric for grid side operators and consumers as charge session cost is typically measured in kWh charged.

The same comparison was done in Figure 13, except the performance metric sorting criteria was changed to range gained (miles). Again, it was seen that the top performing EV changes and EV15 was the top performer. It could be argued that range is the most important performance metric to an EV driver as it is an easily digestible metric for most drivers, however actual on road range can be impact by a number of reasons (temperature, driving behavior, towing, etc.) and so it is important to understand all three metrics (SOC, energy gained, and range) when quantifying charging performance.

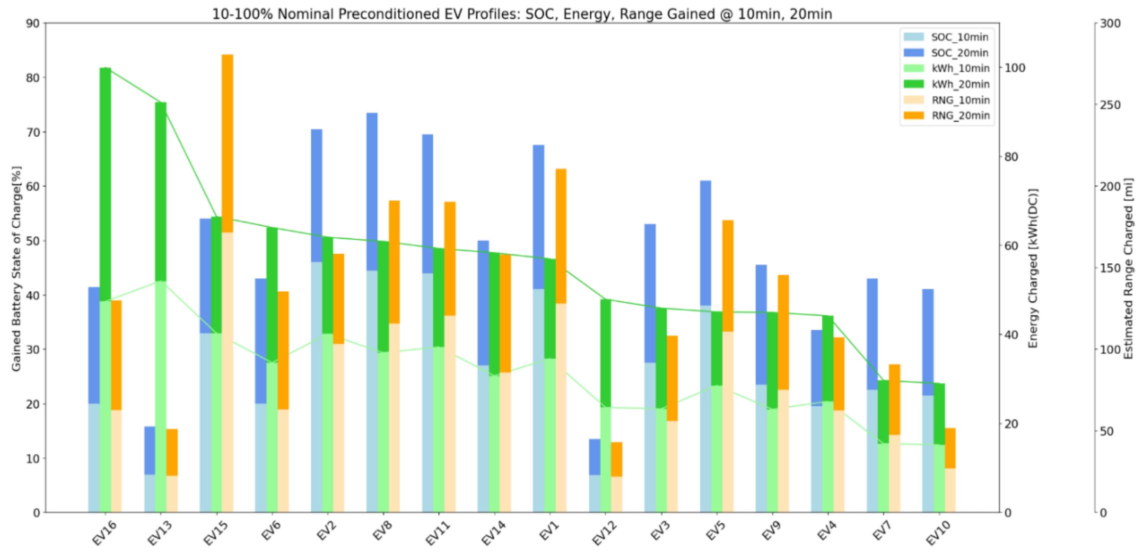


Figure 12: 10-100% Nominal Preconditioned: SOC, Energy, & Range After 10-min & 20-min – kWh Biased

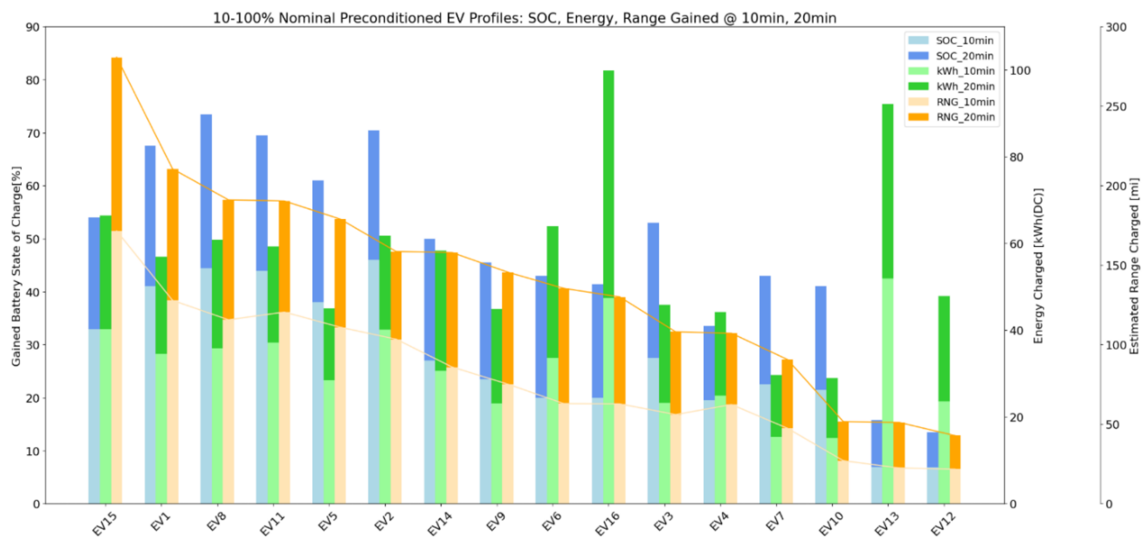


Figure 13: 10-100% Nominal Preconditioned: SOC, Energy, & Range After 10-min & 20-min – Range Biased

Figure 14 and Figure 15 show time required to reach 80%, 100% SOC and 100mi, 200mi range gained; more examples of metrics that would be desirable for consumers when considering/comparing future EV purchases or operating an EV on a long-distance trip. This performance analysis is similar to plots Figure 11, Figure 12, and Figure 13, however now using a slightly different approach where the time to achieve a target metric is analyzed. Also similar to the above analysis, changing between SOC and range bias yields different top performing EVs. It should be noted that these milestones could have been altered to have different goals such as time to 90% SOC or 50-miles, 150-miles, 300miles range added which would have yielded new results for the order of top performing EVs.

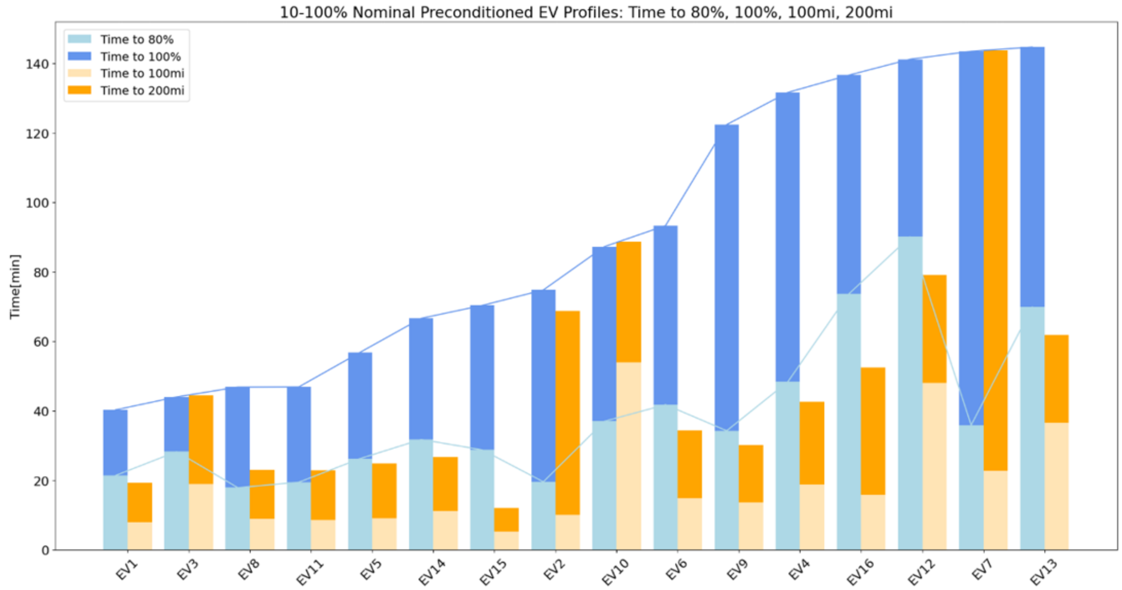


Figure 14: 10-100% Nominal Preconditioned: Time to Gain 80%, 100%, 100mi, 200mi – SOC Biased

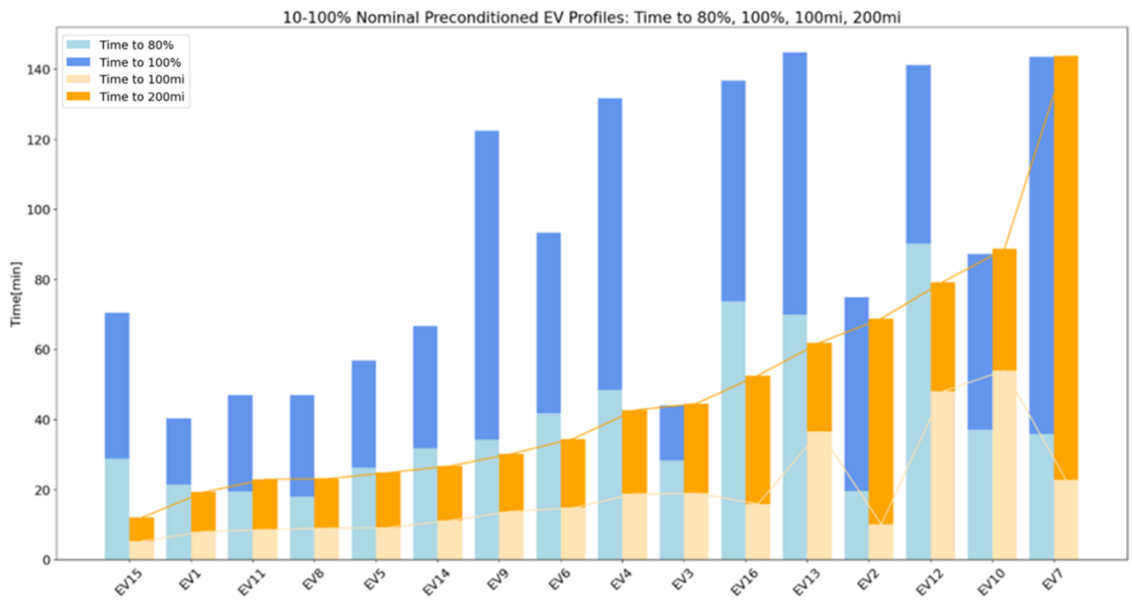


Figure 15: 10-100% Nominal Preconditioned: Time to Gain 80%, 100%, 100mi, 200mi - Range Biased

Analyzing performance in terms of SOC, range, and energy charged is complex and could be presented in multiple ways. It is important for current and future EV drivers, OEMs, grid planners and policy makers, among others, to understand different methods of quantifying and comparing EV charging performance.

Figure 16 examines the relationship between SOC and energy charged. By including the relative battery pack size along with energy charged after 10 minutes and 20 minutes, it highlighted the size of vehicles under test and grid energy required to complete a full 10-100% session. Further, a kWh-based state of charge was calculated and further compared to the reported "Display SOC" that was gathered for SOC analysis.

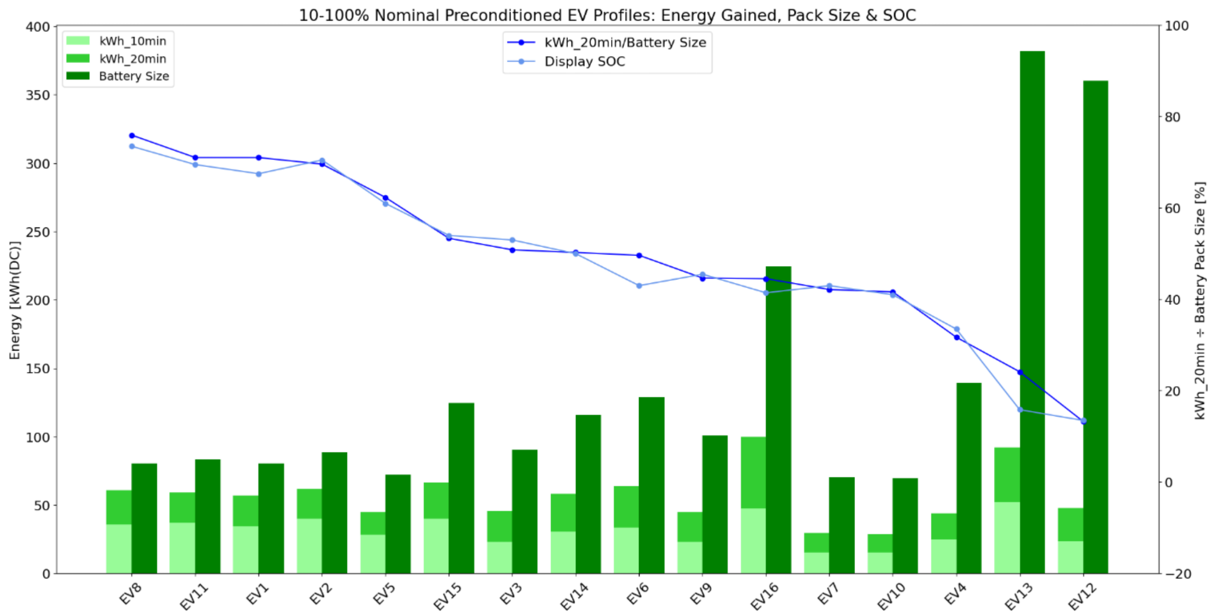


Figure 16: 10-100% Nominal Preconditioned: Energy Gained, Pack Size & SOC

4.2.3 EV Battery Topologies, Current Draw

Battery systems powering EVs play a pivotal role in a DC fast charging session, serving as the key component that drives the charging process. The battery's voltage, state of charge, current capacity, internal resistance, BMS and thermal management systems collectively determine the vehicle charging rate, influencing the overall speed and efficiency of the charging session. Production EV battery topologies in today's market typically have either a <500VDC (400-volt) or a >500VDC (800-volt) Lithium-Ion battery topology. While 400-volt batteries have a more established history within the EV charging industry, vehicles equipped with 800-volt batteries have begun to enter the market.

Next-Gen Profiles EVSE assets used for DC fast charging within the NGP were specified to ensure all production EVs under test could charge at full power without EVSE limitation utilizing state-of-the-art 500A, typically-liquid-cooled cables. However, even at the maximum cable current of 500A a 400-volt vehicle was limited to <250kW DC power. Thermal impacts were an area of consideration when examining current draw, as power (heat) dissipated in a wire increases exponentially with current.

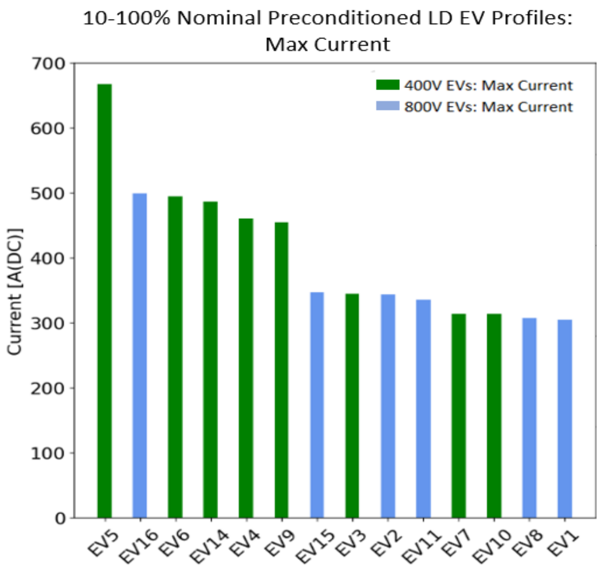


Figure 17: 10-100% Nominal Preconditioned: Maximum Current

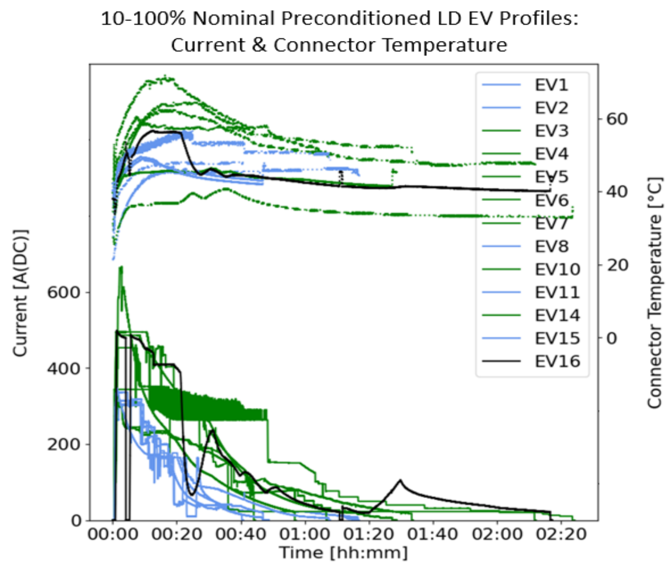


Figure 18: 10-100% Nominal Preconditioned: Current & Connector Temperature

Figure 17 summarizes the light-duty (LD) battery voltage configurations for the NGP EVs under test, showing that the top performing 400-volt vehicles required much higher current draw to compete with 800-volt power levels. Figure 18 highlighted the thermal impacts of higher amperage charge sessions due to lower EV battery voltage topologies. Newly added EV16 is an 800-volt charging topology that accepts ~500A peak current, resulting in a relatively higher connector temperature than the other 800-volt, lower-current EVs.

4.2.4 Power and Current "C" Rates

Another metric used to quantify battery performance in the context of DC fast charging is C rate. The C rate is a ratio of a battery's given current discharge or charge rate in relation to the battery's ampere-hour capacity – a C rate of 1C indicates a current level which would fully charge/discharge the battery in 1 hour (in an ideal example). Figure 19 compares the observed current C rate of all LD and HD EVs under test for the NGP portfolio. The observed C rate calculation was performed by observing the total ampere-hours charged during the entire session, and then comparing the total ampere-hours charged with the peak instantaneous current and average instantaneous current as inputs for peak C rating and average C rating respectively.

$$C_{current\_max} = \frac{A_{peak\_observed}}{Ah_{charged\_observed}} \qquad C_{power\_max} = \frac{kW_{peak\_observed}}{kWh_{charged\_observed}}$$

$$C_{current\_avg} = \frac{A_{average\_observed}}{Ah_{charged\_observed}} \qquad C_{power\_avg} = \frac{kW_{average\_observed}}{kWh_{charged\_observed}}$$

It should be noted that these are estimated values – the total ampere-hours charged during these sessions (as used in the C rate calculations) will be slightly different than the battery's true total ampere-hour capacity, since these tests were ran from 10-100% Display SOC and not true 0-100% Actual SOC. Similarly, total kilowatt-hours charged compared against peak DC power and average DC power was used to calculate power C rating in Figure 20, which yields similar results to that of the current C rating with slight variance.

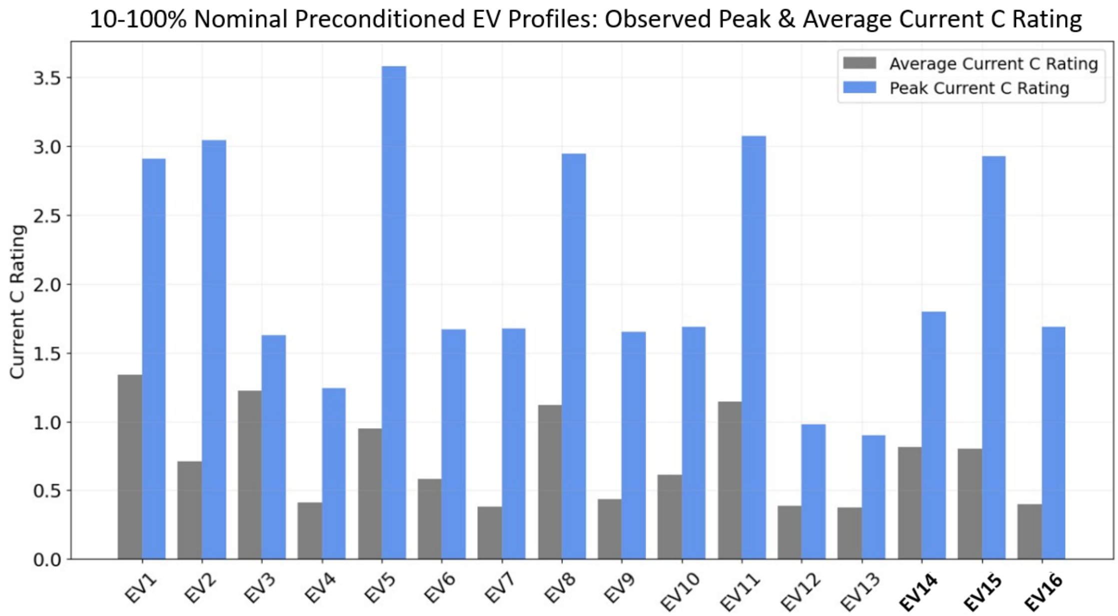


Figure 19: 10-100% Nominal Preconditioned: Observed Peak & Average Current C Rating

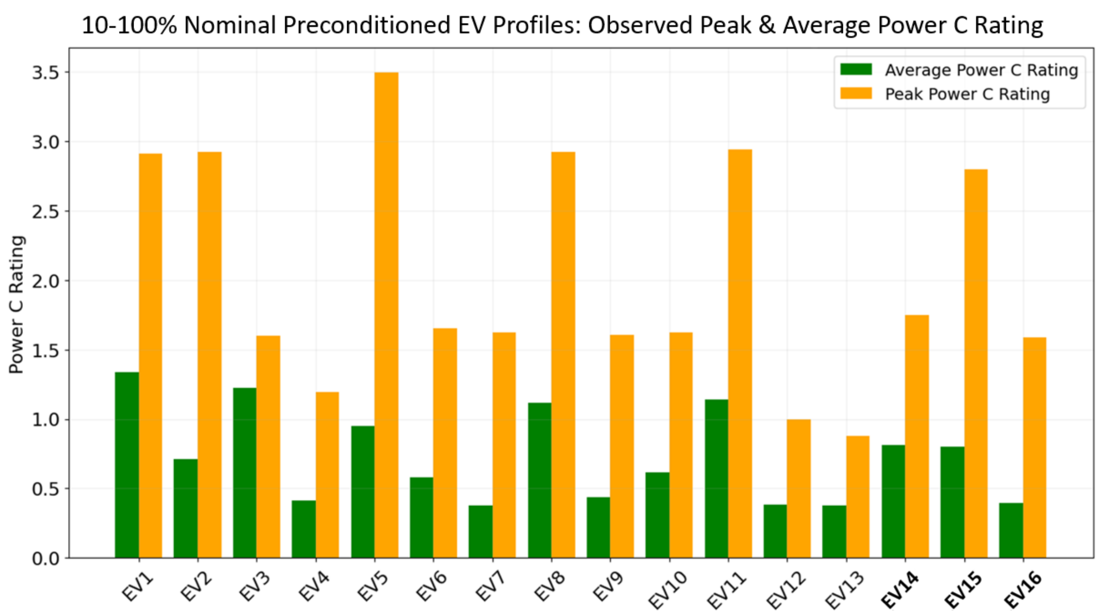


Figure 20: 10-100% Nominal Preconditioned: Observed Peak & Average Power C Rating

4.2.5 Ramp Rates & Charge Session Curtailment

Power during initiation of a DC fast charge session (ramp rate) can be used in quantifying the charging performance of an EV. Figure 21 examined the first 90 seconds of the same power profile curves from Figure 6. Figure 22 depicted the same data after computing ramp rates in kW/second. Results showed EV2 and particularly EV3 had drastically faster ramp rates than the other charge profiles.

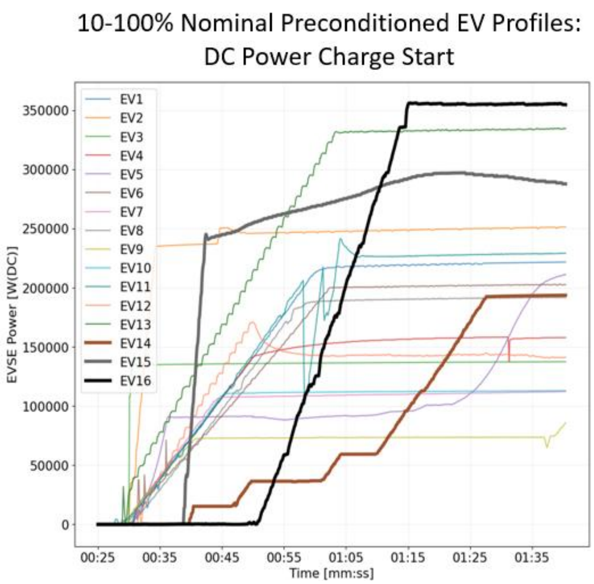


Figure 21: 10-100% Nominal Preconditioned: DC Power Charge Start

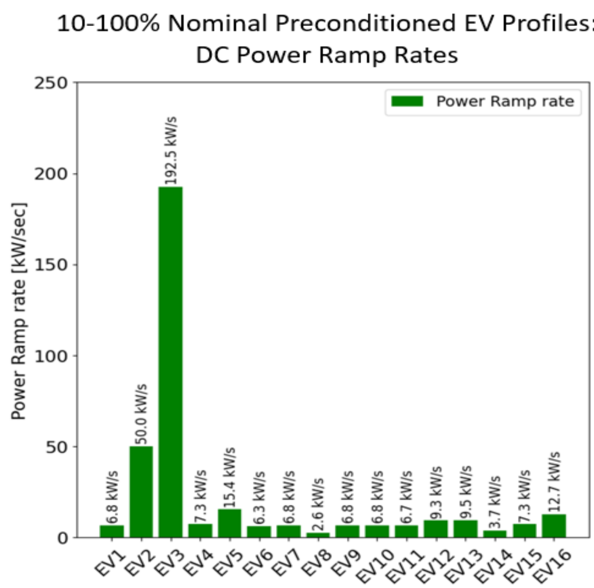


Figure 22: 10-100% Nominal Preconditioned: DC Power Ramp Rates

Power transfer ramp rates were examined in response to open charge point protocol (OCPP) smart charging commands. Figure 23 summarizes the OCPP curtailment testing results containing the EV assets that underwent a 2-minute, 65A curtailment request. EV8 was tested on 2 different EVSE assets under the same conditions to prove results continuity across different charger manufacturers. *SetChargingProfile* OCPP commands were scheduled prior to plug-in whilst the EV/EVSE data acquisition system (DAQ) system recorded 10Hz time-series data as with all other collected profiles. The results showed a very responsive system under ideal laboratory conditions, starting/ending curtailment with high accuracy within seconds of scheduling.

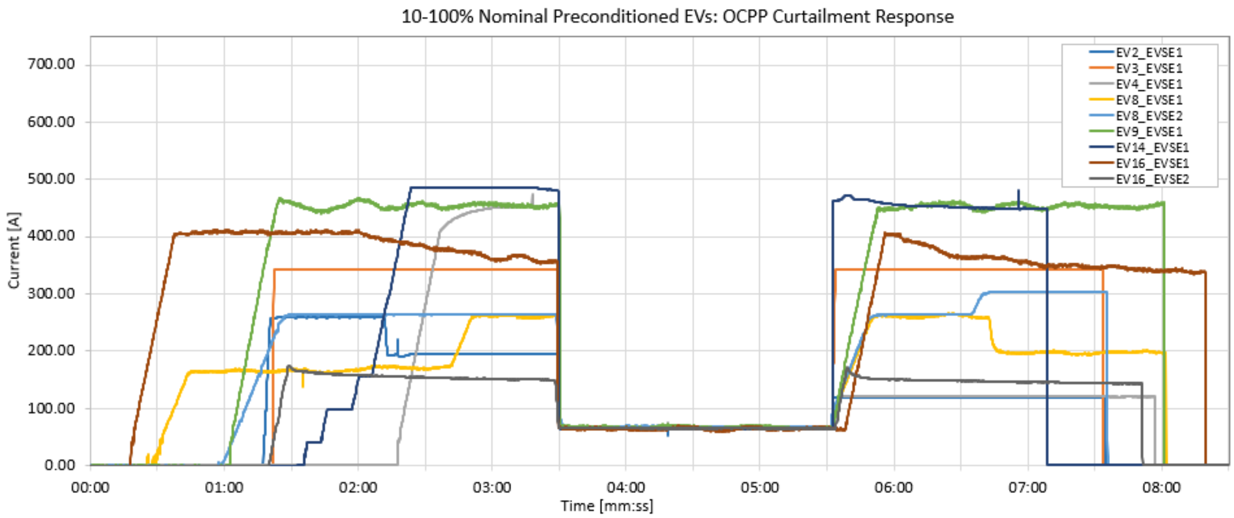


Figure 23: 10-100% Nominal Preconditioned: OCPP Curtailment Curves

Figure 23 is a close-in view of the full OCPP curtailment examining the ramp-down to 65A, which was nearly instantaneous. Figure 25 zooms in on the end of scheduled curtailment where the EV returned to full power operation with no EVSE limitations. This ramp-up was noticeably more prolonged than the ramp-down; approximately 25 seconds required for all vehicles to return to full power operation. This ramp-up rate appeared to follow similar performance to the ramp rates seen in the initial stages of power transfer, presented in Figure 21 and Figure 22

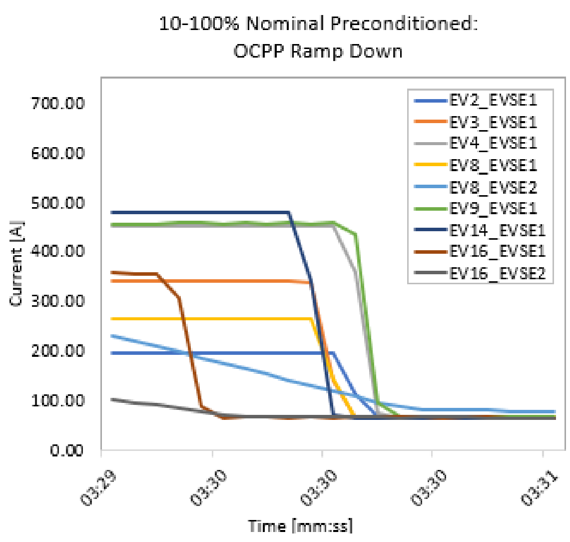


Figure 24: 10-100% Nominal Preconditioned: OCPP Ramp Down

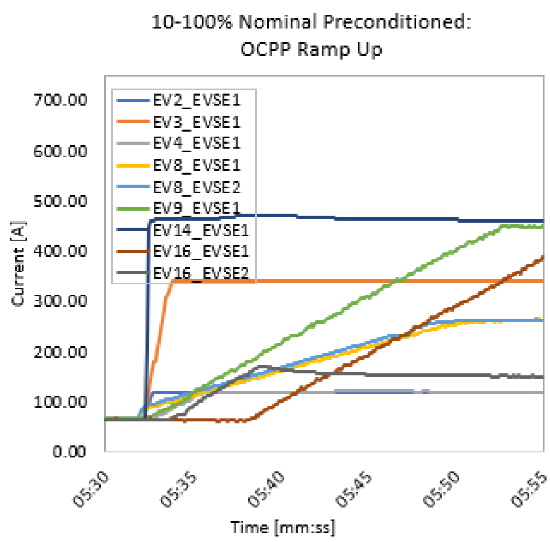


Figure 25: 10-100% Nominal Preconditioned: OCPP Ramp Up

As smart charge management platforms continue to become adopted within industry, it is increasingly necessary to characterize the performance of production EV and EVSEs that incorporate similar control strategies. This work could be further advanced by exploring alternative SCM approaches and boundary conditions such as emergency curtailment, starting charge during a curtailment period, and testing more assets.

4.3 Impacts on Charge Performance

This section examines the impacts that boundary, or "off-nominal" conditions had on charging performance, such as battery SOC, temperature, vehicle conditioning, EVSE limitations, and adapters and boost converters. Whereas section 4.2 analyzed the performance of all EVs under nominal conditions, this section analyzes the performance of two or three 400-volt and 800-volt EVs that underwent all boundary condition testing to highlight the variability even a single EV experienced while charging under different starting conditions. This area of study is especially valuable to deliver realistic expectations for EV charging performance, rather than observing the best possible outcomes through a nominal starting condition charging experience.

4.3.1 Starting Battery State of Charge

The effect of initial SOC as a boundary condition on EV charging profiles was explored. Figure 26 shows three 800-volt EVs that underwent three charge sessions with similar starting conditions of nominal temperature and vehicle preconditioning, but with the starting SOC values ranging from 10%, 25%, and 50%. These three starting SOC values were chosen to explore the variance below 50% SOC with the goal of targeting realistic consumer starting conditions. Generally, as starting SOC increases, peak power values and time spent during peak power decreases. Intuitively, one would expect that the charge time to 100% would have been the lowest when starting at 50% SOC, however the 50% starting charge session was the shortest charge session for only one (EV2) of the three EVs evaluated.

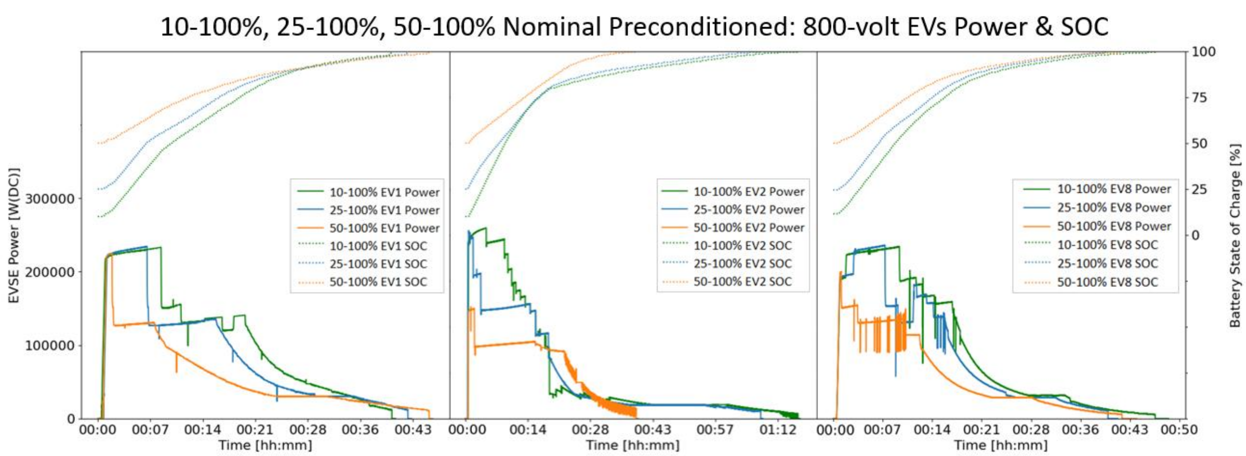


Figure 26: 10, 25, 50-100% Nominal Preconditioned: 800-volt EVs Power & SOC

Figure 27 shows the same starting SOC boundary condition testing performed with three 400-volt EVs under similar nominal temperature and vehicle preconditioning initial conditions. These vehicles exhibited less variation in peak power across the range of starting SOCs, except for EV5 that yielded a much lower peak power from the 50% starting SOC than its 10% and 25% counterparts.

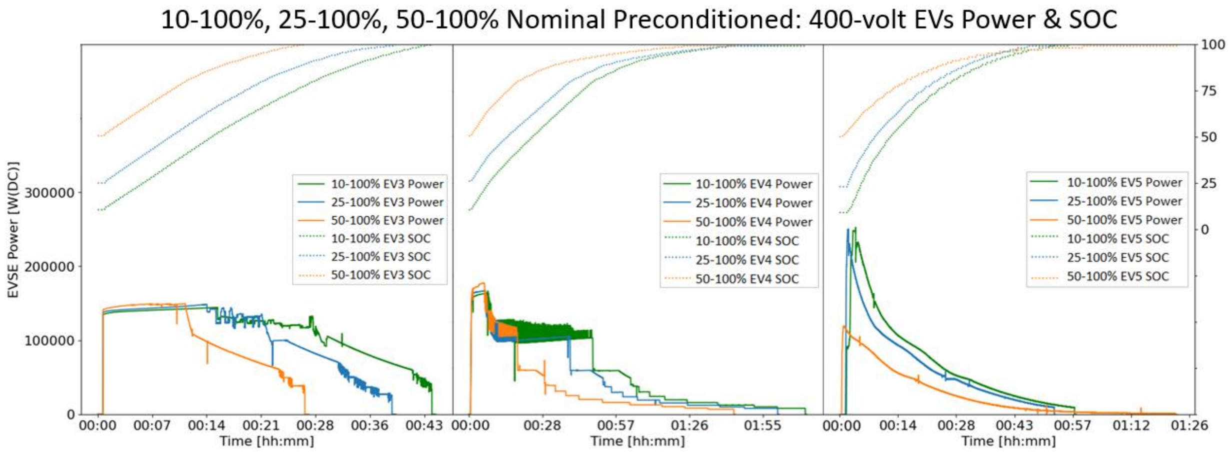


Figure 27: 10, 25, 50-100% Nominal Preconditioned: 400-volt EVs Power & SOC

It was observed that vehicles capable of high-power charging above 200kW required much more specific starting conditions to achieve vehicle rated peak power. Battery limitations, OEM charging strategies, and EV driver behavior are all factors to be considered when analyzing the optimization of starting SOC in DC fast charging.

4.3.2 Starting Battery Temperature & Conditioning

The effect of initial EV battery temperature as a boundary condition on EV profile capture was explored at starting temperatures of nominal (23°C), hot (40°C), and cold (-7°C).

Figure 28 highlights the thermal impacts on charge performance for three 800-volt EVs that underwent nominal, hot and cold weather testing. These charge sessions ran from 10-100% had similar performance at the nominal (green) and hot (blue) conditions, achieving the OEM-rated peak power levels in both scenarios. High temperature charging was observed to have a negligible effect on the shape of the charging profiles for the evaluated vehicles. There was a noticeable drop-off in performance when observing the cold weather (orange) charge sessions, most of which were unable to charge above 100kW or until battery temperatures had risen.

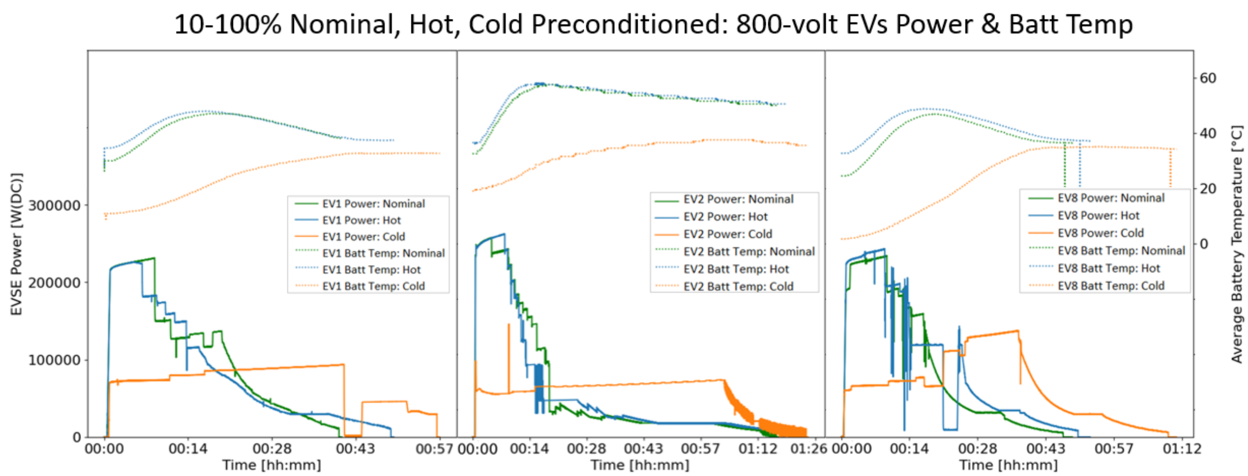


Figure 28: 10-100% Nominal, Hot, Cold Preconditioned: 800-volt Power & Battery Temp

The same analysis was conducted for 400-volt vehicles seen in Figure 29 with similar results to the tested 800-volt vehicles but with less variation. EV3 had a noticeably lower peak power and longer charge time during the cold session than the other boundary conditions, however EV4 was able to perform with higher peak and lower charge time during the cold session. This could have been due to EV4 having some combination of a larger pack size than EV3 (nearly 50% larger battery pack), differing battery chemistry, software optimization, lower margins of design safety, and/or better thermal management. Only nominal and hot conditions were captured for EV5 but were included to further show the similarity in performance between the two conditions.

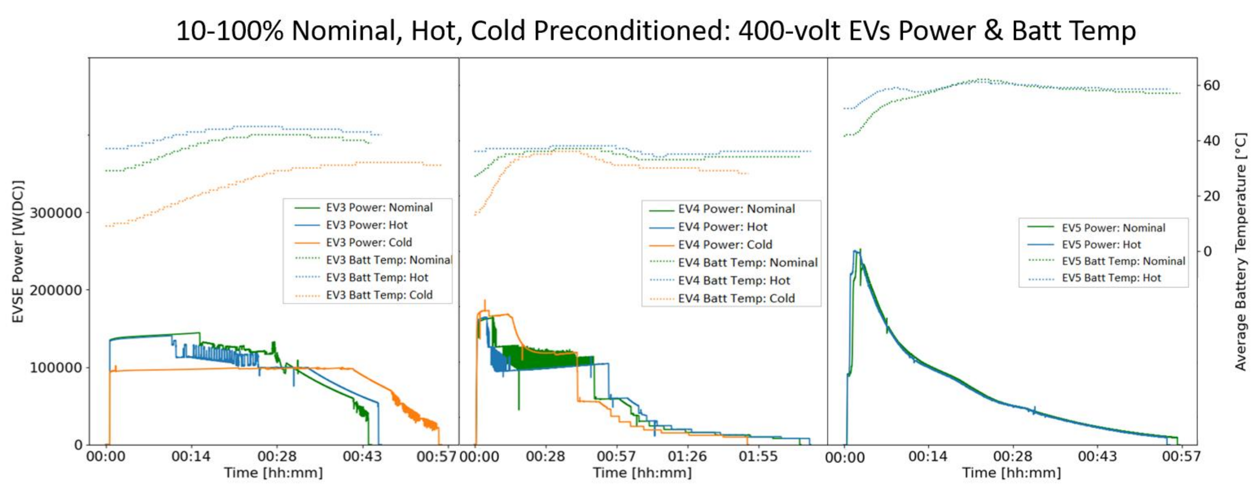


Figure 29: 10-100% Nominal, Hot, Cold Preconditioned: 400-volt Power & Battery Temp

Vehicle conditioning was explored for its effects as a boundary condition on EV charging profiles. To achieve required initial conditions, vehicles were soaked for a minimum of four hours in temperature-controlled environments or outdoor weather conditions and EV pack internal temperatures were confirmed through vehicle diagnostic data. Upon reaching the targeted starting temperature after a stationary soak, a charge session was immediately conducted to fulfill the "soaked" vehicle test condition. The pre-driven vehicle condition was set by driving the vehicle on a 40–60-minute route after reaching battery starting temperature from the vehicle soak. This condition impacted the starting temperature of the battery, but more accurately emulated real-world scenarios of on-demand charging at public chargers. Many production EVs have a preconditioning feature that preheats or precools the battery to optimal temperature when GPS anticipates charging at a public DC fast charging station, allowing for ideal starting temperature and power results upon plug-in. Performing this drive cycle with or without the utilization of preconditioning and conducting a charge session fulfilled the "preconditioned" vehicle condition.

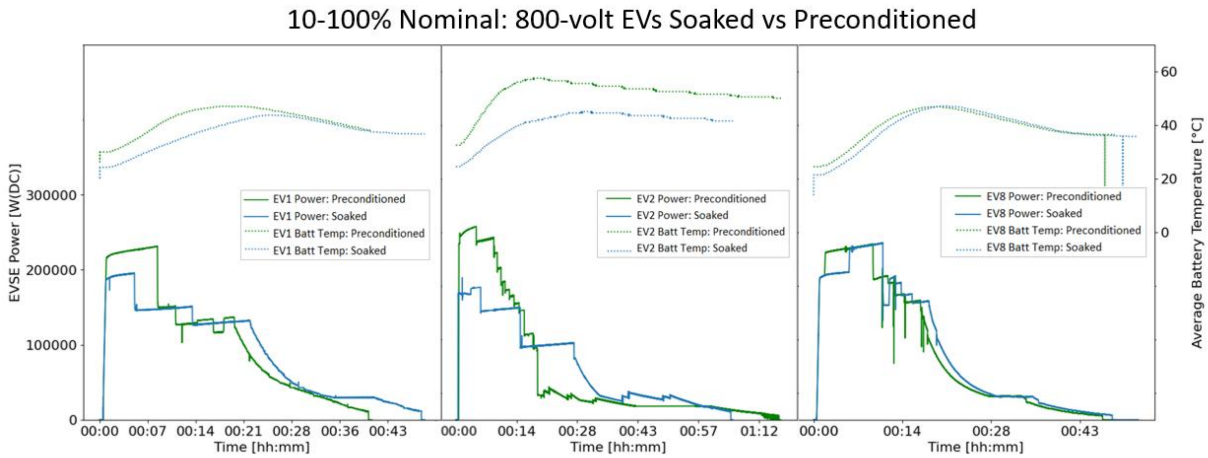


Figure 30: 10-100% Nominal: 800-volt EVs Soaked vs Preconditioned

Figure 30 depicts the results of 800-volt vehicles under nominal temperature 10-100% charging conditions, comparing the effects of soak and precondition on charge performance. Results showed that the preconditioned case (green) resulted in a higher peak power and shorter charge time to 100% for some vehicles. Average battery temperature was also included to highlight the variance in preconditioning across EVs. Figure 31 illustrates the same results for 400-volt EVs, which demonstrated less variance in peak power than the 800-volt results seen in Figure 31.

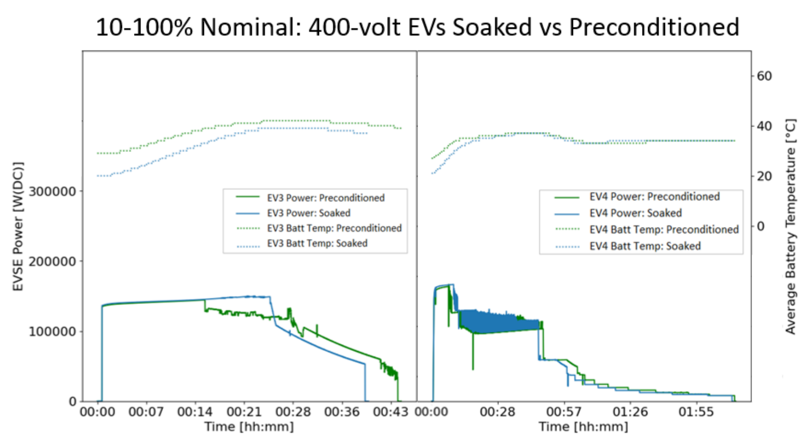


Figure 31: 10-100% Nominal: 400-volt EVs Soaked vs Preconditioned

It was observed that some EVs could only achieve manufacturer-rated charge performance under a small subset of these testing conditions, whereas others were able to achieve their ratings throughout many of them.

4.3.3 EVSE Power & Current Limitations

For the eighteen profile capture conditions explored, the charging equipment was specified to be a non-limiting factor to accurately characterize the full power charging capabilities of the EVs under test. This required full power dual cabinet 350kW EVSE equipment, capable of 50-1000VDC at 500A max rating. However, given that EVSE equipment is not always operating at its full capability, a useful boundary condition to explore was EVSE-limited charge sessions. Nominal conditions required a dual cabinet topology operating at full power, whereas for EVSE-limited conditions the DC fast charging infrastructure was limited to a single cabinet topology, only being able to employ 50% of the installed power modules.

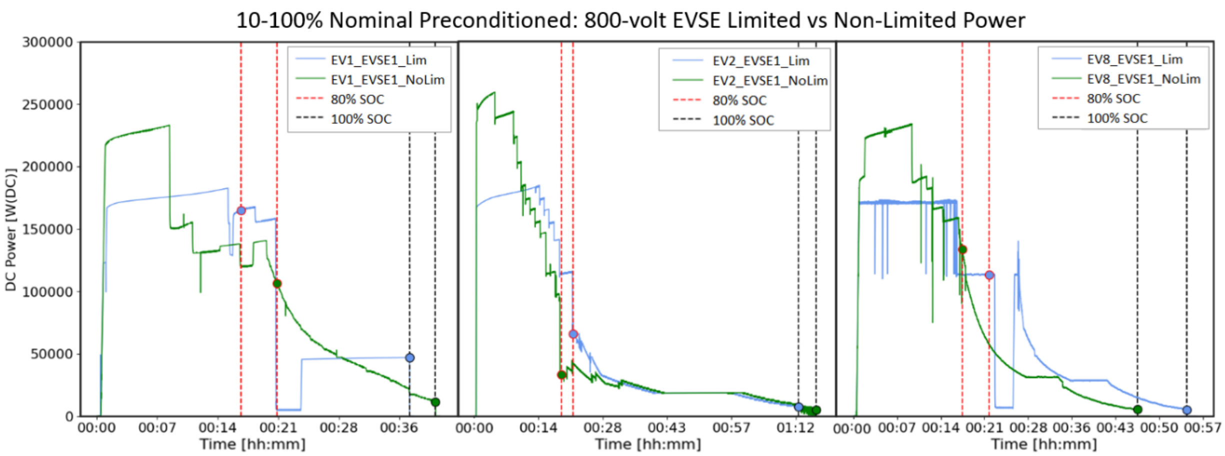


Figure 32: 10-100% Nominal Preconditioned: 800-volt EVSE Limited vs Non-Limited Power

Figure 32 depicts three 800-volt vehicles that underwent EVSE limited testing, with comparison to their nominal non-limited power profiles. Results showed the blue curves (limited) were operating at a much lower power level, but it should be noted that low power plateaus had longer durations than the peak of the green (non-limited) profiles. The hypothesized outcome from this boundary test was that when charge power is limited, the session would require more time to reach the 80% SOC milestone but could complete a 100% SOC charge in less time due to reduced thermal strain on the EV battery. The results showed much variation between the three 800-volt vehicles. During the EVSE limited conditions compared to the EVSE full capability conditions, EV1 reached both 80% SOC and 100% SOC quicker, EV8 reached both 80% SOC and 100% SOC slower, and EV2 gave the hypothesized result of reaching 80% SOC slower but achieved 100% SOC quicker.

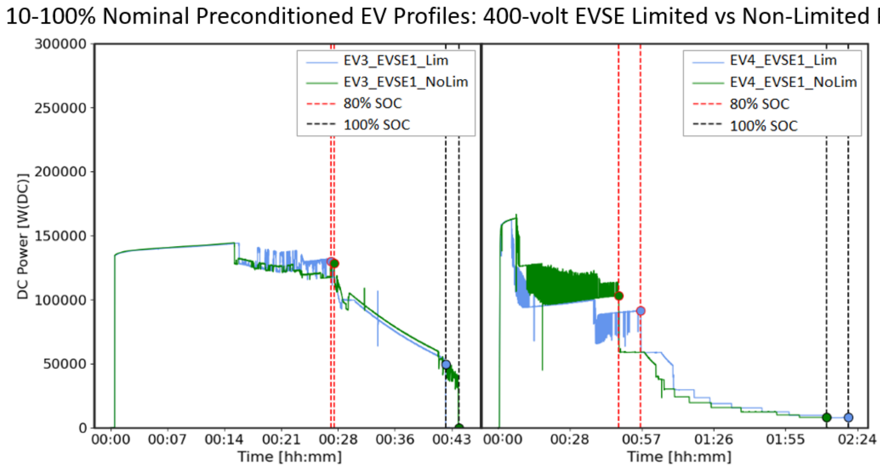


Figure 33: 10-100% Nominal Preconditioned: 400-volt EVSE Limited vs Non-Limited Power

Figure 33 illustrates examples of two 400-volt vehicles that underwent EVSE limited boundary condition testing. The selected 400-volt EVs were unaffected by the limitations of a single cabinet EVSE topology; the EVSE equipment used for DC fast charging was still capable of producing 500A at 400-volt with a single cabinet, and so results remained essentially unchanged between the NGP-defined "EVSE Limited" and non-limited test case, yielding very similar power curves.

4.3.4 Adapters, Voltage Limitations, Boost Converters

Exploration of adapters and boost converters was added to the project scope towards the end stages of testing. Charging adapters help bridge the gap between charging standards by enabling EVs with different charging ports to connect to and utilize a DC fast charging station. These adapters are useful but can be a limiting factor in terms of charging performance. The goal of this testing was to compare charging power using the same EV on two chargers: one with a matching handle type, and the other requiring an adapter. Figure 34 shows 400-volt EV4 that underwent 10%, 25%, and 50% starting SOC profiles captured under nominal preconditioned conditions. Results showed that the peak power was limited across all 3 adapter profiles, however the overall charge time and power curves acted very similarly. Achieving both 80% and 100% charge times for the 400-volt vehicle had a 3–5-minute variance across adapter and non-adapter profiles.

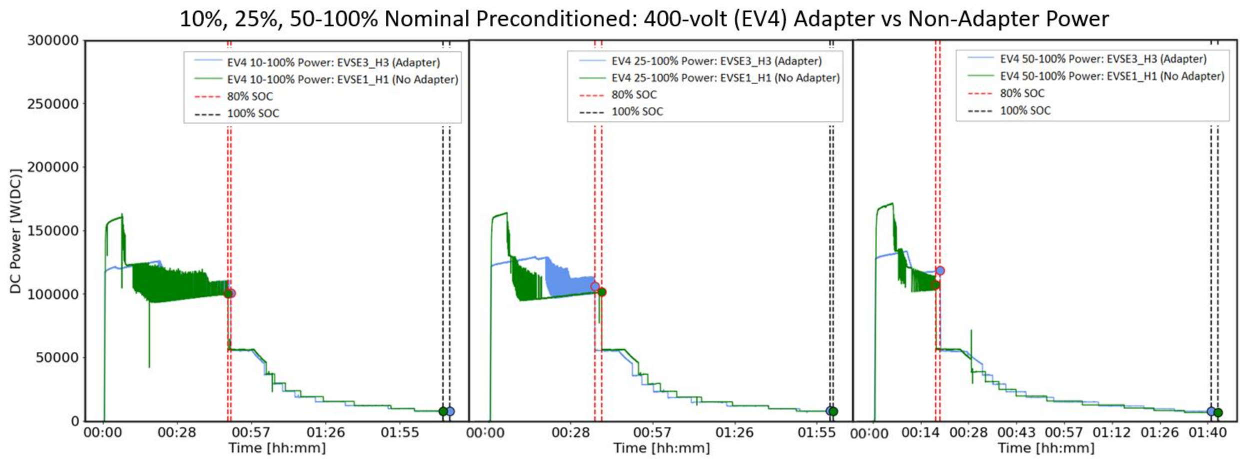


Figure 34: 10, 25, 50-100% Nominal Preconditioned: 400-volt Adapter vs Non-Adapter Power

Figure 35Figure 35 depicts the results of 800-volt EV11 under test on EVSE3 and EVSE1. This test was similarly conducted to that of Figure 34 Figure 35; however, the adapter was not the only limiting factor. It should be noted that EVSE3 had a voltage range of 50-500V, forcing EV11 to utilize the on-board voltage boost converter to allow for 800-volt charging. Results showed a reduced charge power and far longer charge time, reaching 80% and 90% SOC values in over double the time.

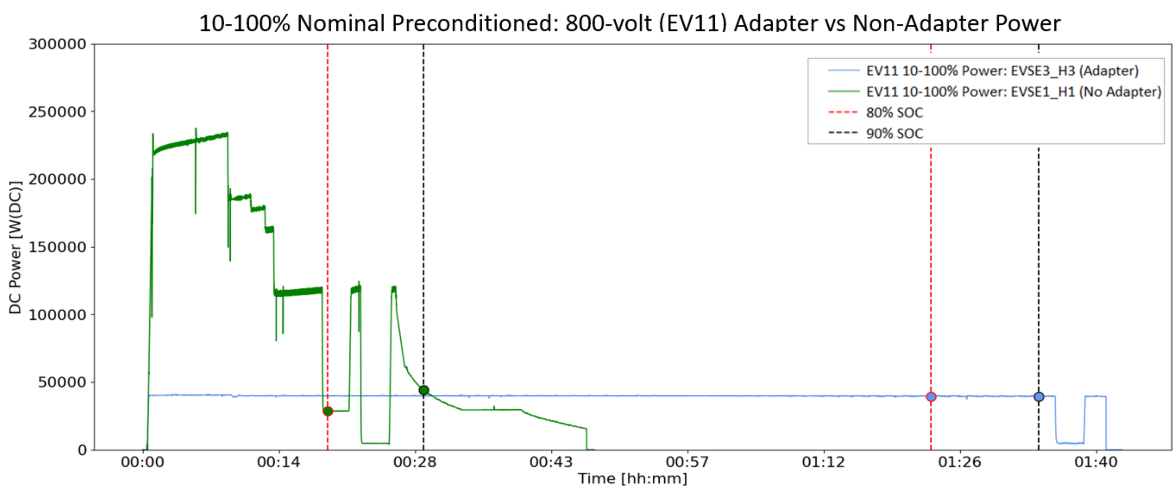


Figure 35: 10-100% Nominal Preconditioned: 800-volt Adapter vs Non-Adapter Power

Figure 35 shows the results of EV16 under test with EVSE1 and EVSE2. EVSE1 was limited to a maximum DC voltage of 500V while EVSE2 was allowed to run as normal. EV16 does not utilize a boost converter on-board to match a higher than nominal voltage. Instead, it changes battery pack configuration to achieve different operating voltages. Results show that the peak power achieved in the 400V charge session is approximately half of the peak power achieved in the 800V charge session indicating that the peak power is current-limited in the 400V charge session. This results in much higher charge power during approximately the first 20 minutes of the charge session in the nominal (not voltage-limited) case. The vast difference in the first portion of the nominal and voltage-limited charge sessions eventually turns into a near-identical charge power by the 90-minute mark. Despite not reaching the same higher charging speeds as the nominal session, the voltage-limited session results in a similar 100% charge time- it can be seen that the 80% and 100% charge times are within 3 minutes of each other.

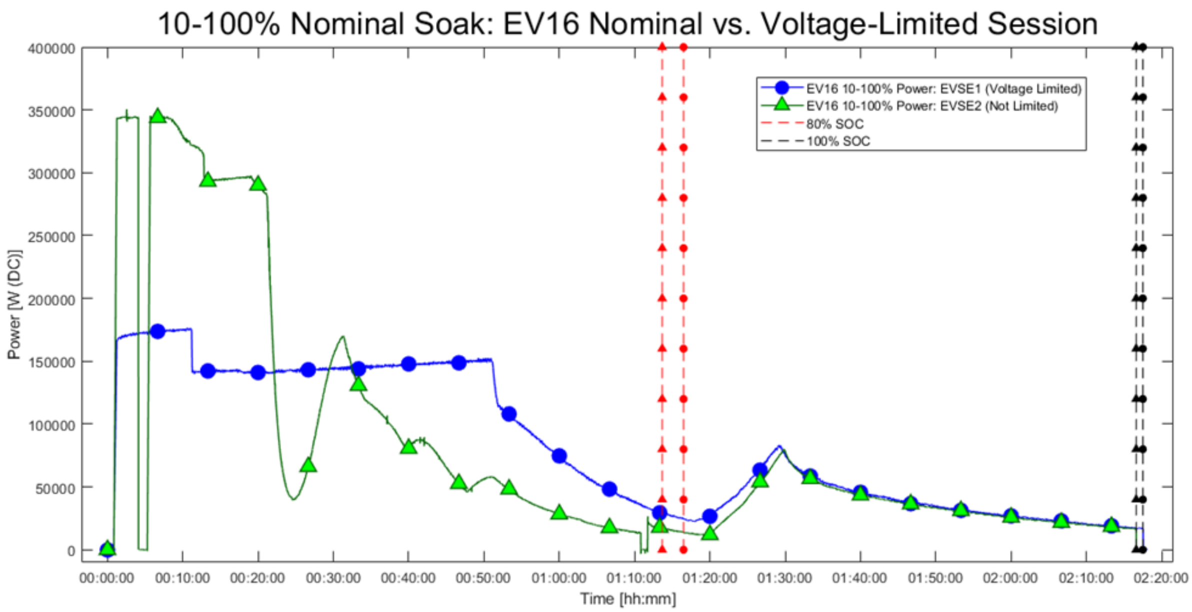


Figure 35: 10-100% Nominal Soak: Nominal vs Voltage-Limited

The differing nature of these charge curves leads to a very different user experience in roughly the first hour of the charge session. Table 6 shows how the EV reaches the same SOC faster in the nominal session until 85% SOC. This means that a charge to 50% SOC during a long-distance trip will cost 18 mins on a nominal charger. In contrast, the same charge session will cost an additional 13 mins on a voltage-limited charger for a total of 31 mins. This also reiterates the advantages of having a traction battery with a >500V architecture in the context of charge times for quick charge sessions.

Table 6: 10-100% Nominal Preconditioned: Performance Details

SOC [%]	No EVSE Limitation	EVSE Voltage-limited (500V)
	Time [hh:mm]	Time [hh:mm]
13	0:00	0:00
25	0:07	0:09
40	0:13	0:22
50	0:18	0:31
80	0:54	1:03
85	1:23	1:23
90	1:36	1:34

100	2:17	2:18

Figure 36 showed how the SOC increased over time during the two charge sessions. Both sessions were nearly identical after the 85% SOC mark. It also illustrated the diminishing returns of keeping the charger plugged in for long duration. For example, in case of the nominal session, ~150 miles of range were recuperated within the first 30 mins of the session. This dropped to only 50 miles of range being added in the next 30 mins, and 20 miles in the following 30 mins. For contrast, in the voltage-limited session, 100 miles were added in the first 30 min, 90 miles added in the next 30 min and only 30 miles added in the final 30 min. It was seen that charging at the vehicle's nominal voltage carried a significant advantage in the first 30 minutes of the charge session. However, that advantage was significantly diminished after 1 hour, and by 90 minutes, it had essentially eliminated. For this EV, the data demonstrated that for short charge sessions (e.g., those done en-route as part of a road trip), it's important for drivers to be able to charge at the nominal voltage, however, for longer charge sessions of 90+ minutes (e.g., those done while the driver is shopping, or eating a meal), the impact of a voltage-limited session was minimal.

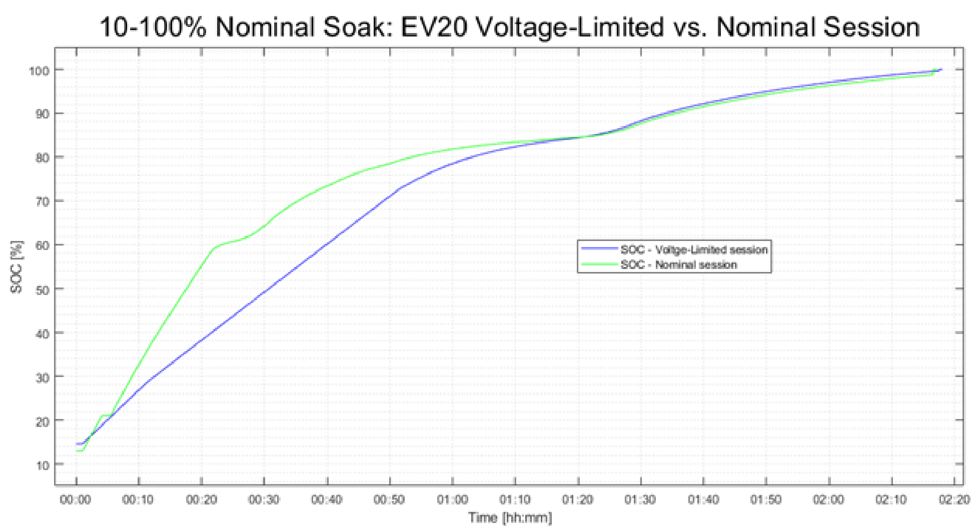


Figure 36: 10-100% Nominal Soak: EV20 Voltage-Limited vs Nominal Session

4.4 Future Battery Technologies

Research is underway to improve extreme fast charging (XFC) with lithium-ion batteries. The XCEL project: eXtreme fast charge Cell Evaluation of Lithium-ion Batteries project is a collaborative laboratory effort to build and test innovative battery technologies, which aims to gain an understanding of the main limitations during ultra-fast charge using a combined approach involving the building of cells with various designs.

As part of XCEL, cells are built in Argonne National Laboratory's Cell Analysis, Modeling, and Prototyping (CAMP) facility and are then tested at both Idaho National Laboratory (INL) and Argonne under various operating conditions and under different charging protocols with the aim of identifying the onset of plating, quantifying the extent of the problem, and determining parameters and test data for mathematical models (TAPS, 2022)[3].

XCEL battery characterization tests were performed similar to the NGP-defined nominal starting conditions, but from 0-100% rather than 10-100% and soaked rather than preconditioned. Figure 36 shows the 800-volt battery achieved peak power levels of ~330kW at currents above 430A. The battery attained power levels above 290kW for most of the charge, and only dropped below 290kW at ~92% SOC.

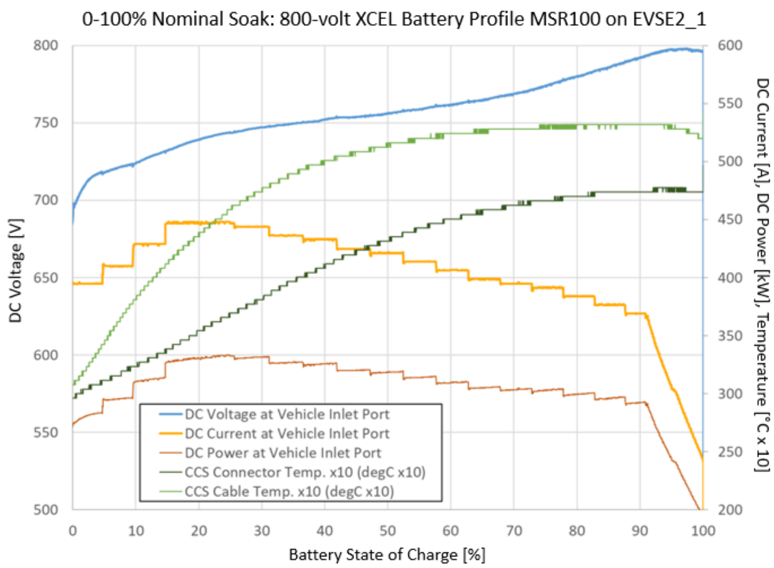


Figure 36: 0-100% Nominal Soak: 800-volt XCEL Battery Profile MSR100 on EVSE2_1

Figure 37 and Figure 38 compare the XCEL data against a top performing 800-volt LD EV that charged under nominal conditions. The XCEL battery reached much higher peak power levels with a much-reduced charge time. It should be noted that battery pack size of the XCEL was smaller than EV2's (nearly 50%), and that the energy gained within the first 5-10minutes of charge was comparable.

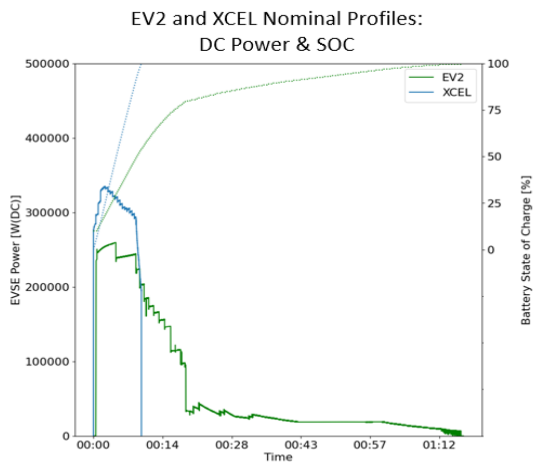


Figure 37: EV2 and XCEL Nominal Profiles: DC Power & SOC

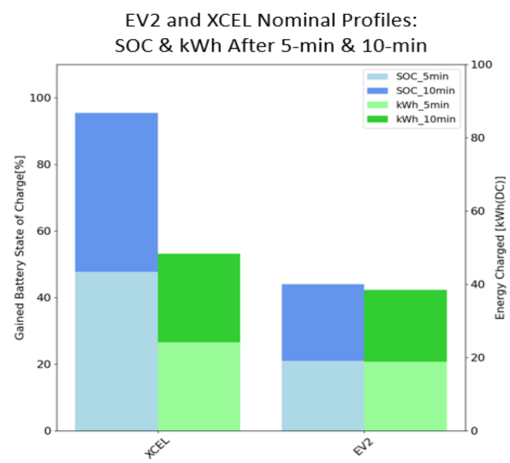


Figure 38: EV2 and XCEL Nominal Profiles: SOC & kWh After 5-min & 10-min

4.5 Using EV Profiles to Improve Grid Modelling Applications

In 2024, the scope of the NGP project has expanded to include the integration of the extensive EV charge profile data collected into grid modeling platforms developed by other projects. This extension aims to enhance the effectiveness and accuracy of these platforms by providing real-world, time-series data that reflects the dynamic behavior of EVs under various charging conditions, such as power demand, state of charge (SOC), and temperature variations. As the adoption of electric vehicles grows, accurately modeling the impact of their charging patterns on the grid becomes increasingly important for optimizing grid operations, predicting energy demands, and informing infrastructure planning.

By incorporating our detailed charge profiles into these modeling efforts, we are helping to create more robust and realistic simulations, ultimately supporting the development of a more efficient and resilient energy grid. This section provides a summary of ANL's IEEE-37 HIL grid model, INL's Caldera grid model, and NREL's EVI-X grid model platforms, discussing how NGP EV charge profiles were integrated and the value they added.

4.5.1 ANL's IEEE-37 HIL Grid Model

A study was developed for a MATLAB-based Hardware-In-the-Loop (HIL) model developed by ANL to analyze the real-world impact of XFC charging profiles on the grid frequency, the study of which is published in the IEEE archive and can be accessed using (DOI: 10.1109/ITEC60657.2024.10599002). Using the EV charge profiles captured for a variety of "next-generation" EVs at different start SoC and temperature conditions, a database of 93 profiles were used to develop a MW-level charging site scenario.

This scenario envisioned a charging site with EVSE usage that was mixed; for a small business' EV fleet charging that is opened for public use when fleet charging is undesired during business hours. Figure 39 shows one possible site load profile obtained where the small business EVs charge outside of business hours and during business hours the chargers are available for public use. For charge profiles outside of business hours (i.e. curves "1") multiple NGP EV charge profiles are stacked representing multiple EVs charging at once. Similarly, during business hours (i.e. curves "2") one or multiple NGP charge profiles are stacked representing public charging. Many different iterations of this site load are possible with randomness of user behavior considered to emulate unique charger utilization rates.

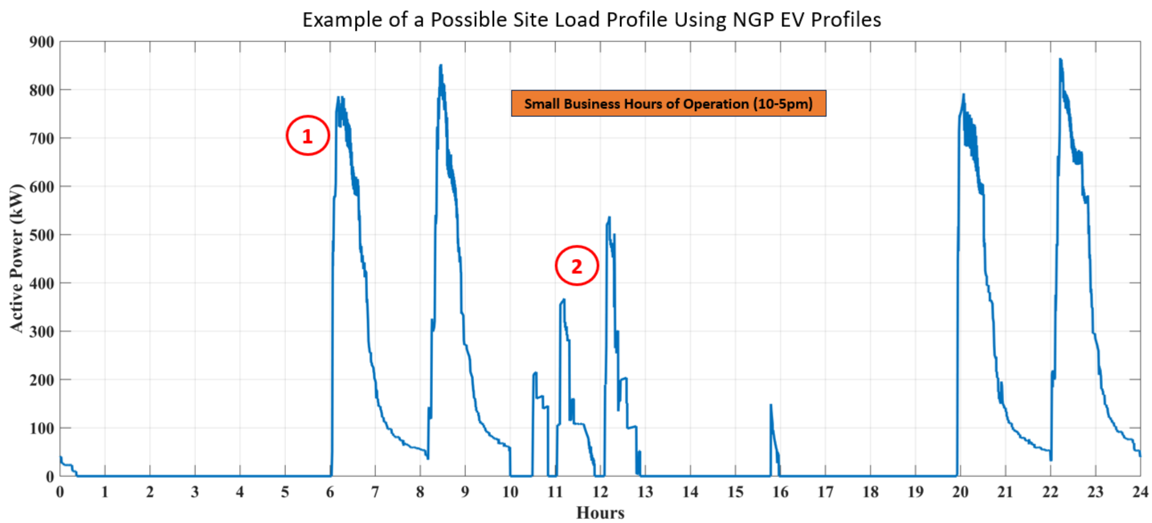


Figure 39: Example of a MW-Site Load over 24-hours

After developing the MW-site profile, two real-world XFCs and BESS have been connected to a real-time digitally simulated modified IEEE 37-bus distribution grid and run on an Opal-RT real-time digital simulator. The modified IEEE 37-bus distribution grid is modeled, which runs in real-time. The full HIL system is shown in Figure 40, and the IEEE-37 grid network in Figure 39.

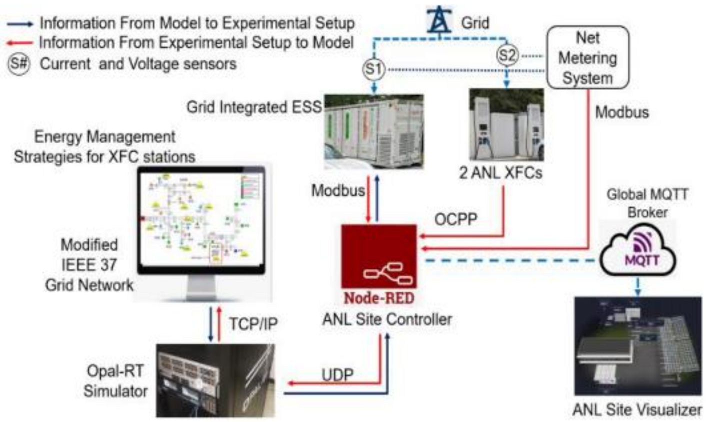


Figure 40: HIL System Overview

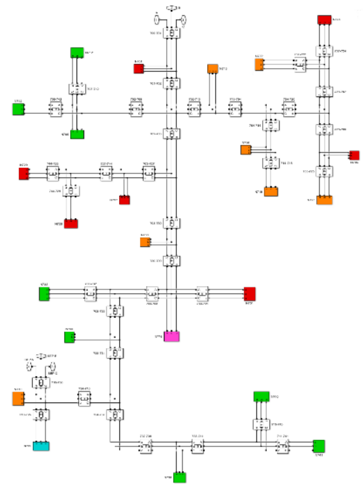


Figure 41: Modified IEEE-37 Grid Network

Both the real XFCs interacted with the system on one node. Other grid nodes used residential, commercial, and MW depot charging sites developed earlier with the real-world NGP charging profiles. A live charging session for an 800VDC battery architecture EV was run on one of the real XFCs during the experiment. The impacts of such loads on the grid frequency as frequency deviation and rate of change of frequency (RoCoF) were captured and analyzed.

The model developed using these real-world NGP EV charge profiles were further used to design an optimal control strategy that could determine the amount of injected or absorbed active power from the co-located BESS to mitigate the effect of running a large number of XFCs clusters on the grid frequency and rate of change of frequency.

4.5.2 INL's Caldera Grid Model

Caldera is a set of software tools developed by INL to model charge events, both at a local EV-EVSE level and at a region-level where thousands of charge events are modeled for broad grid analysis efforts. Currently the Caldera software produces idealistic power profile curves specific to a particular EV type (with a particular battery chemistry, capacity, and max C-rate) and EVSE type, where it is assumed that the charge event occurs with ideal battery temperatures and conditions, resulting in a smooth ramp-up and ramp-down of power. However, the newly collected NGP data makes it clear that these idealistic assumptions are far removed from what is typically seen in practice, where control algorithms take multiple factors into account including battery temperature, causing the power level to jump up and down throughout the charge event. See Figure 42, Figure 43, Figure 44, and Figure 45.

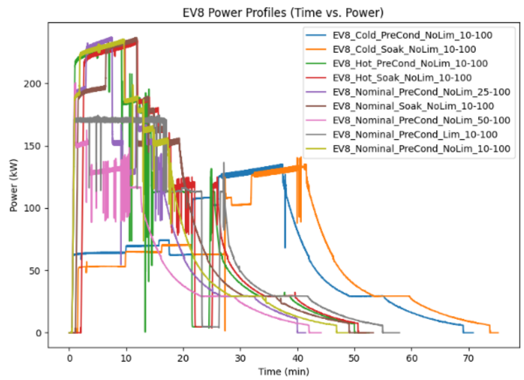


Figure 42: NGP Collected Power Profiles for EV8

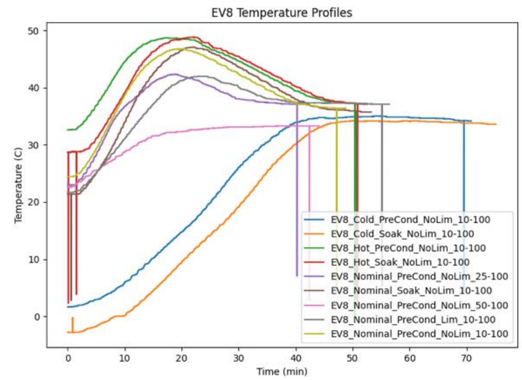


Figure 43: NGP Collected Temperature for EV8

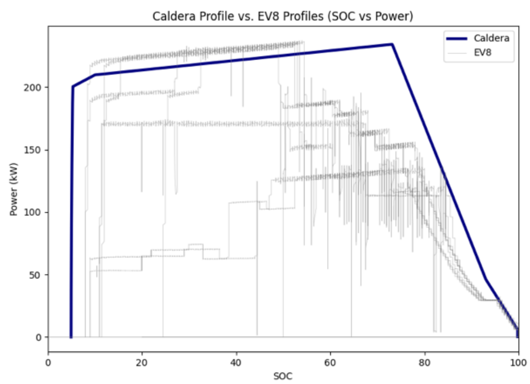


Figure 44: Comparing Caldera Power vs SOC Profile to NGP EV8 Power vs SOC Profiles

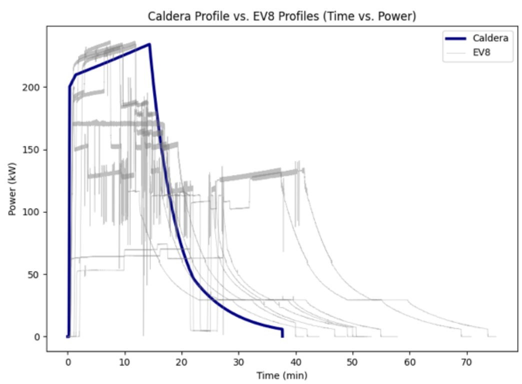
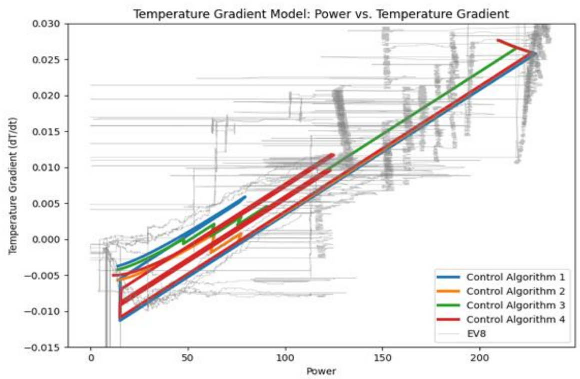


Figure 45: Comparing Caldera Power vs Time Profile to NGP EV8 Power vs Time Profiles

To address this challenge, preliminary work was completed to develop an algorithm that would approximate the battery temperature throughout a charge event and adjust the power level to maintain nominal temperatures. In this preliminary study, we focused on EV8. The NGP data was used to train an ordinary least squares (OLS) regression model that allowed the temperature gradient of the battery to be predicted during a charge event based on the power level, temperature, elapsed time, and battery SOC. The EV8 NGP data was analyzed to produce a set of five coefficients, forming a linear function which can be used predict the temperature gradient throughout the charge event given the four input parameters:

$$\frac{dT}{dt} \approx c_0 + c_1 P + c_2 T + c_3 t + c_4 S$$

where P is the power in kilowatts, T is the temperature in Celsius, t is the elapsed time in seconds, and S is the state of charge (SOC) of the battery. See Figure 46 Figure 46.



c_0	0.002023113475
c_1	0.00017361318
c_2	-0.00043137616
c_3	0.00000256712548
c_4	0.00000322413435

Figure 46: Slice of Temperature Gradient Linear Model Output Data for Power vs Temperature Gradient during Simulations Compared to NGP EV8 Data and Respective Coefficient Values, Constructed using scikit-learn

A simulation of the charge event begins with an input starting temperature and by following an idealistic power profile curve, predicting the temperature gradient and updating the temperature each timestep of the charge event. A simple control algorithm is used to adjust the power level by jumping to various pre-computed idealistic profile curves at different C-rates (produced beforehand using the original Caldera tool). An example is shown in Figure 47. Multiple variations of this control algorithm were written and compared to the original NGP data, as shown in Figure 48.

More work needs to be done to verify this method on other vehicle types. Success is dependent on two important pieces: (1) building a sufficiently accurate temperature gradient model from the available NGP data, and (2) finding a control algorithm that approximates the behavior of the vehicle. The temperature gradient model is dependent on the quality of the NGP testing and data-collection. This preliminary study focused on the EV8 because the data collected for it was most complete. The control algorithm is more challenging because most vehicle charging control algorithms are proprietary, and it is difficult to produce a simulated control algorithm that perfectly matches the behavior of the given vehicle. To accurately model a vehicle, a process of trial and error may be needed to find a control algorithm that best matches the behavior observed in the vehicle data.

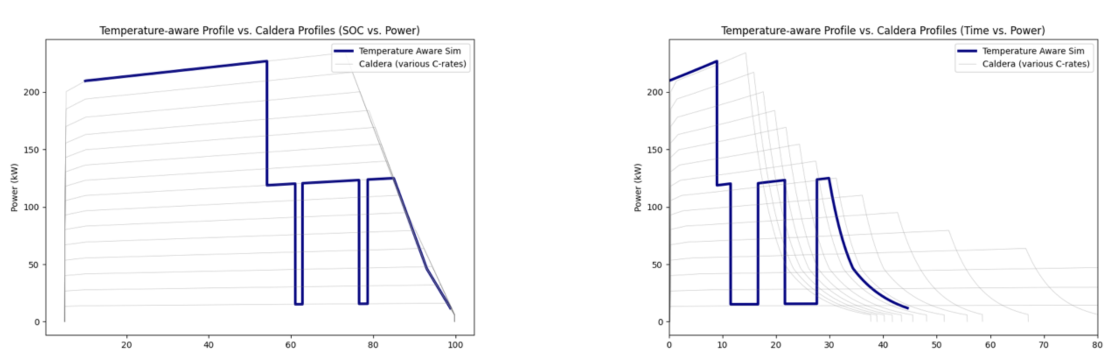


Figure 47: Temperature-Aware Power vs SOC and Power vs Time Profile Simulated by Jumping Between Computed Caldera Profiles to Maintain Nominal Battery Temperature using Control Algorithms

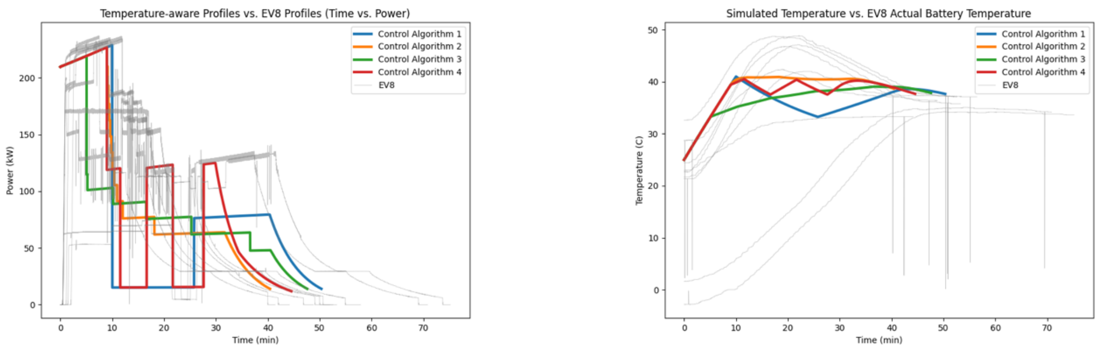


Figure 48: Four Versions of a Simple Power-Level Control Algorithm, Each Adjusting the Power Level During the Charge Event to Maintain Nominal Temperature.

4.5.3 NREL's EVI-X Grid Model

EVI-Rental Model

NREL is developing Electric Vehicle Infrastructure – Rental Car (EVI-Rental), a tool which models the electrification of an airport rental car fleet. Off-nominal temperature NGP EV charging profiles were used to help improve the tool by modeling the seasonal effects of different temperatures on charging sessions. Additionally, test procedures developed under Next-Gen Profiles were also used to perform some characterization of a lower-power DC charger representative of the type used by an airport rental fleet.

EVI-Ensite Model

Electric Vehicle Infrastructure – Energy Estimation and Site Optimization (EVI-EnSite) is a tool developed by NREL to perform studies of different EV charging station configurations, designs, and usage scenarios. Users can configure a station with a different number of ports, power levels, control strategies, and model the performance under different conditions, such as with a different mix of vehicles and arrival schedules. Vehicle agents within this model currently integrate charge acceptance curves to realistically model the changing power demand during a charge session, however, the curves do not currently incorporate the impact of varying temperature conditions on the vehicle's power demand profile. EV profile data from NGP is being integrated into this model to add additional functionality which will enable users to more accurately model charging power demand in varying hot, cold, and nominal temperatures.

IEEE 2030.13 Modeling Efforts

IEEE 2030.13 is a standard which provides guidance for designing EV fast charging station management and control systems for stations which can integrate with local energy storage and generation (e.g., battery energy storage and PV generation)[4].As part of an effort to improve this standard, an NREL team used EV and EVSE profiles collected in different conditions as part of Next-Gen Profiles to create realistic test cases (e.g., different vehicles at different SOCs arriving at different times to a multi-port EV charging station in various weather conditions). These test conditions were then used to more realistically test the impact of various control schemes in different conditions and are currently being used to inform the development and validation of different control strategies.

5 References

[1] Thurston, S., Wells, L., & Argonne National Laboratory. (2023). *EV Profile Capture: A Next-Gen Profiles Project report*. https://publications.anl.gov/anlpubs/2024/01/187073.pdf

[2] Khader, M. (2017). Precise constant current regulation helps advance fast-charging. *Technical Article*.https://www.ti.com/lit/ta/sszta38/sszta38.pdf?ts=1737598724671&ref_url=https%253A%252F%252Fwww.google.com%252F

[3] Transportation and Power System (TAPS) Division, 2022. "Argonne News - Argonne Collaborative Center for Energy Storage Science: Extreme Fast Charge", Argonne National Laboratory. https://www.anl.gov/access/research/projects/extreme-fast-charge.

[4] IEEE SA. (n.d.). *IEEE Standards Association*. IEEE Standards Association. https://standards.ieee.org/ieee/2030.13/10407/

6 Appendix: EV Profile Detailed Datasheets

EV1_22_LD_>500V

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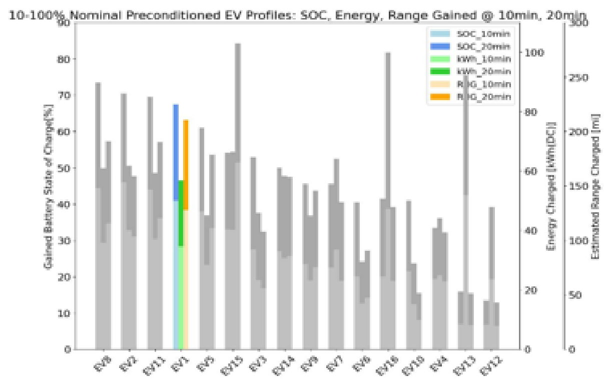
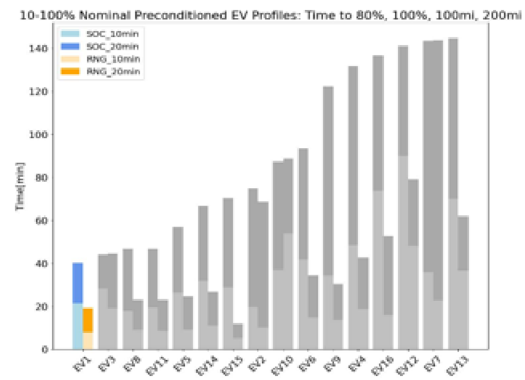
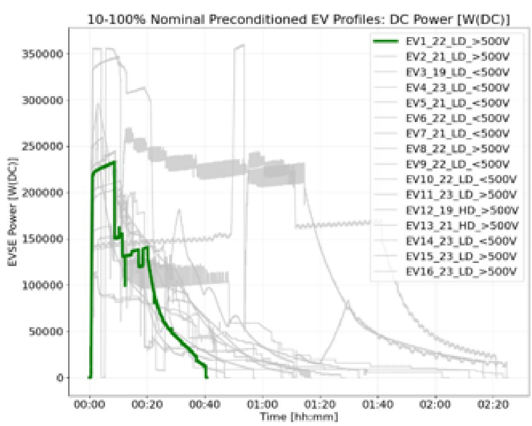
Vehicle Description	
Identifier	EV1
Model Year	2022
Vehicle Type	Light Duty
Nominal Charging Voltage	> 500VDC
Rated Usable Energy	50-100 kWh
Rated Max Charge Power	200-250 kW
Rated Charge Time (10-80%)	~20 min
Rated Range	200-250 miles
EVSE Charged On	EVSE1_H1

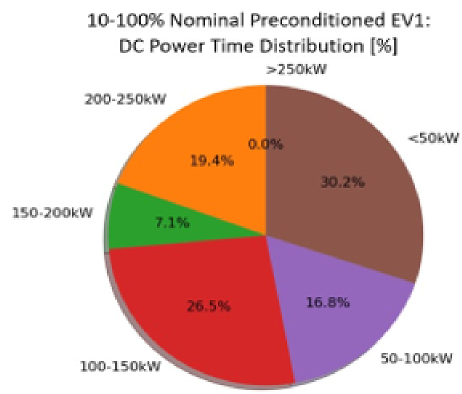
SOC, kWh, Range





DC Power





Testing Conditions	SOC: 10-80%				SOC: 10-100%						
	Time [min]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	Time [min]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	I_{peak} [A]	P_{peak} [kW]	Battery $Temp_{peak}$
Nominal PreCond	0:21	217	164	59	0:40	142	109	73	~300	~250	47°C
Nominal Soak	0:25	186	140	59	0:48	119	91	73	~250	~200	44°C
Hot PreCond	0:23	198	149	57	0:49	115	87	71	~300	~250	48°C
Hot Soak	X	X	X	X	X	X	X	X	X	X	X
Cold PreCond	0:38	113	83	52	0:57	93	70	67	~100	~100	33°C
Cold Soak	0:39	107	79	52	0:59	90	68	67	~100	~100	31°C

EV1_22_LD_>500V

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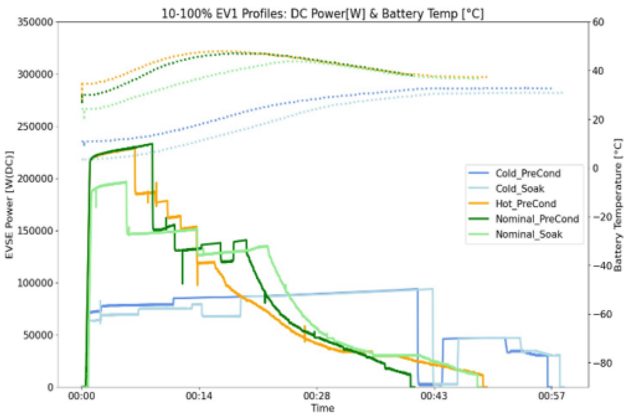
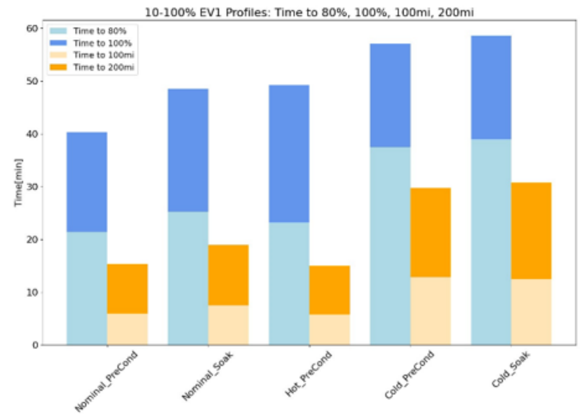
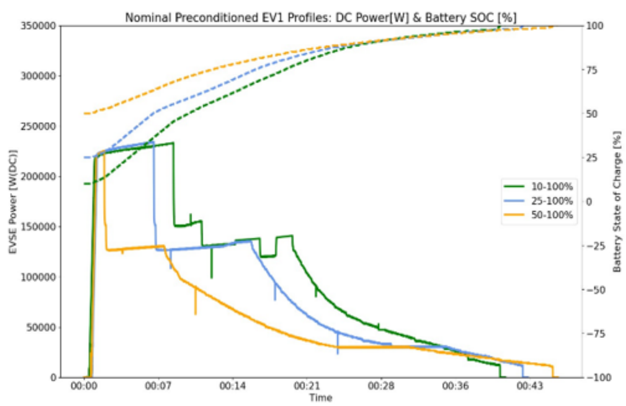
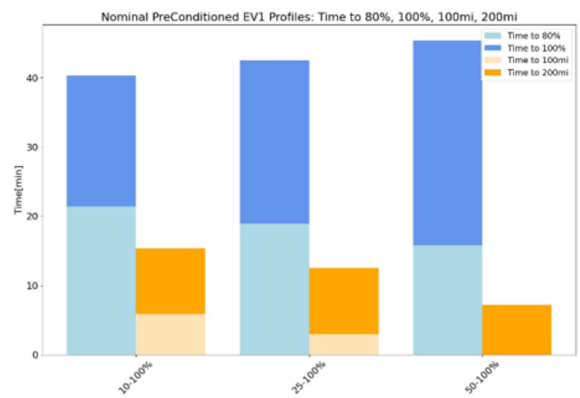
Temperature & Conditioning Variance



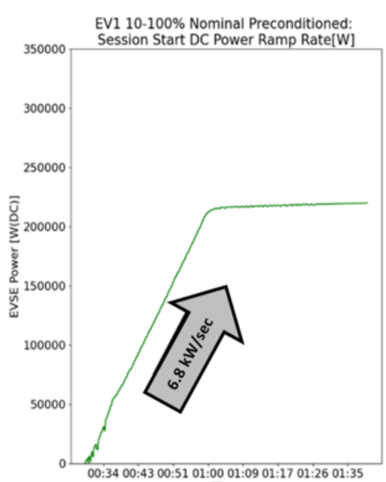


Start SOC Variance

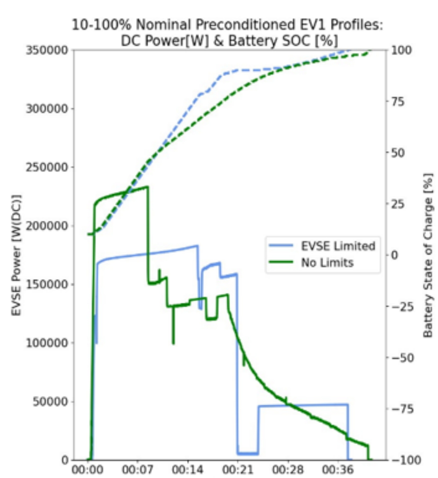




Ramp Rate & SCM



EVSE Limited



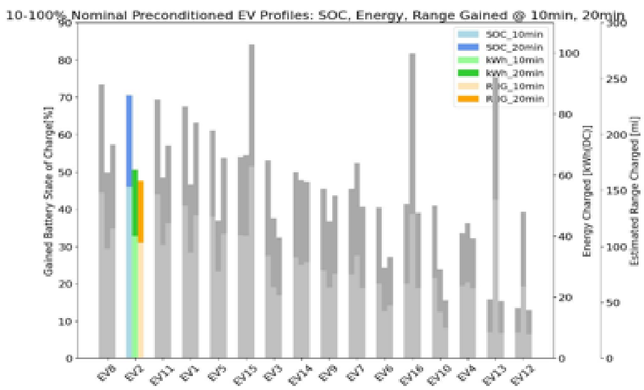
Adapters/Converters

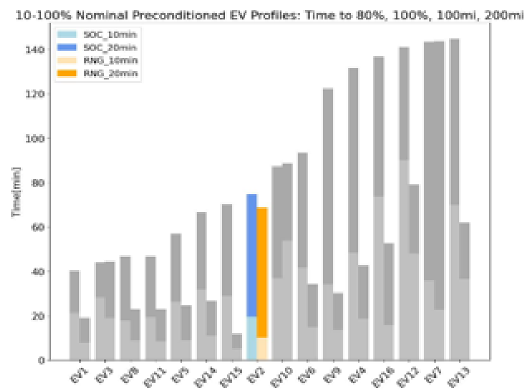
EV2_21_LD_>500V

Page (1/2)

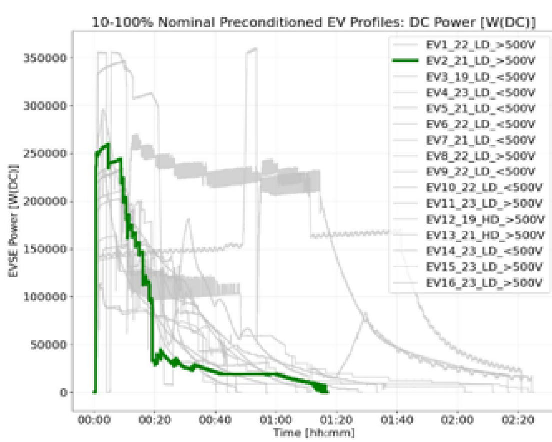
Vehicle Description	
Identifier	EV2
Model Year	2021
Vehicle Type	Light Duty
Nominal Charging Voltage	> 500VDC
Rated Usable Energy	50-100 kWh
Rated Max Charge Power	250-300 kW
Rated Charge Time (10-80%)	~20 min
Rated Range	250-300 miles
EVSE Charged On	EVSE1_H1

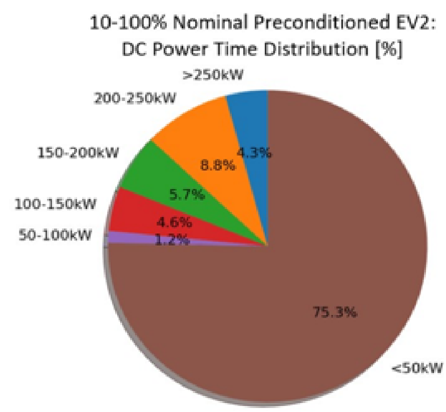
SOC, kWh, Range





DC Power



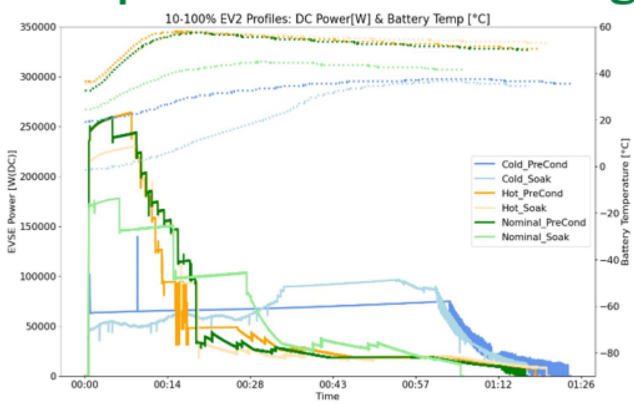


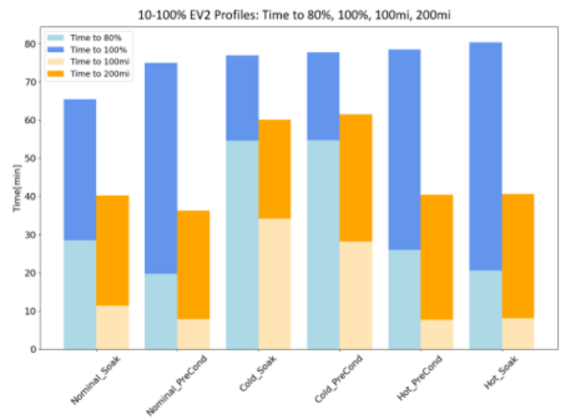
Testing Conditions	SOC: 10-80%				SOC: 10-100%						
	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	I_{peak} [A]	P_{peak} [kW]	Battery $Temp_{peak}$
Nominal PreCond	0:19	240	186	61	1:15	82	65	81	~350	~250	58°C
Nominal Soak	0:29	167	128	61	1:05	94	73	79	~250	~200	45°C
Hot PreCond	0:26	182	141	61	1:18	78	60	79	~350	~250	58°C
Hot Soak	0:21	222	170	58	1:20	74	57	77	~300	~250	58°C
Cold PreCond	0:55	89	67	61	1:17	79	61	79	~200	~150	38°C
Cold Soak	0:55	93	70	64	1:17	83	64	82	~100	~100	37°C

EV2_21_LD_>500V

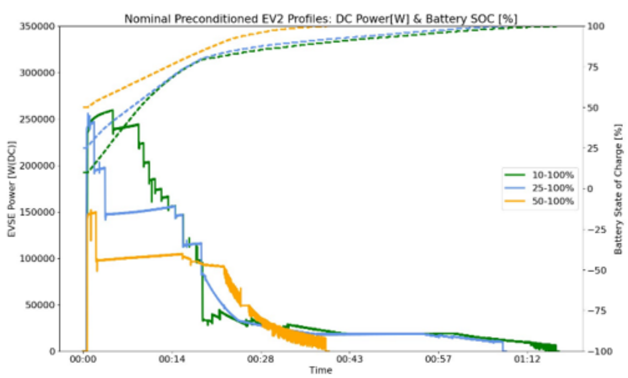
Page (2/2)

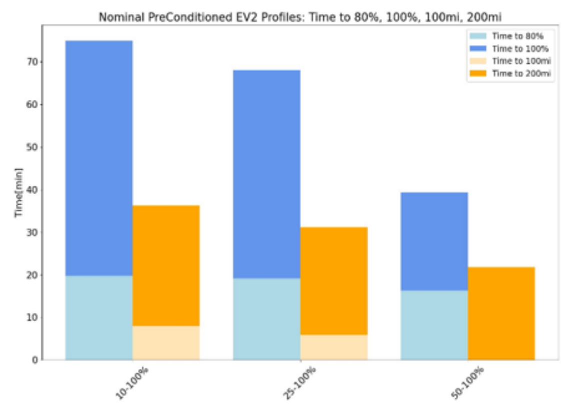
Temperature & Conditioning Variance



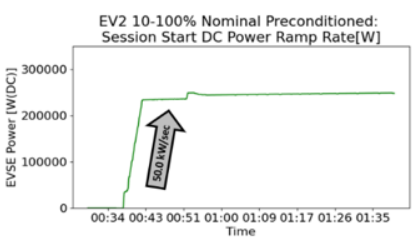


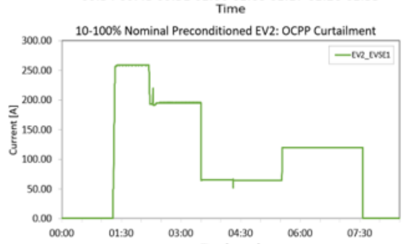
Start SOC Variance



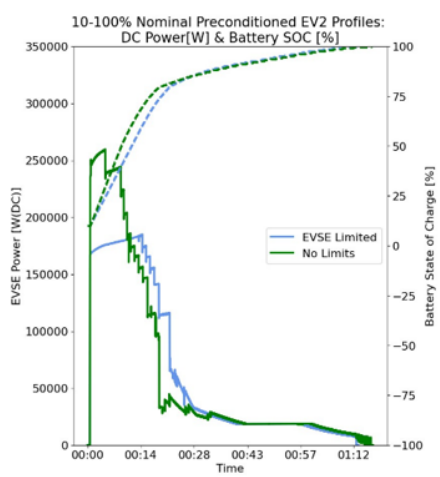


Ramp Rate & SCM





EVSE Limited



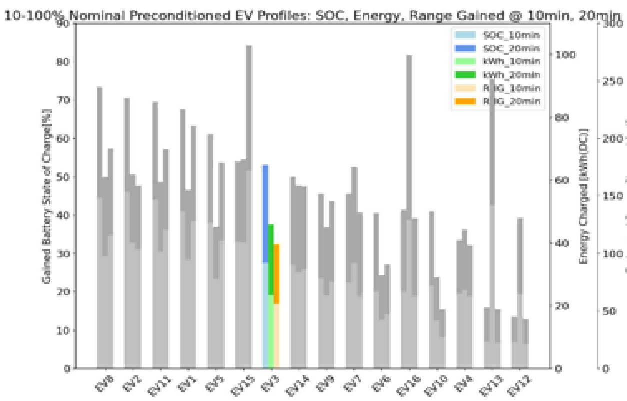
Adapters/Converters

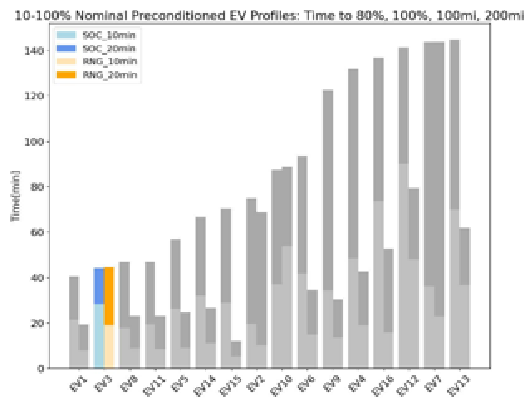
EV3_19_LD_<500V

Page (1/2)

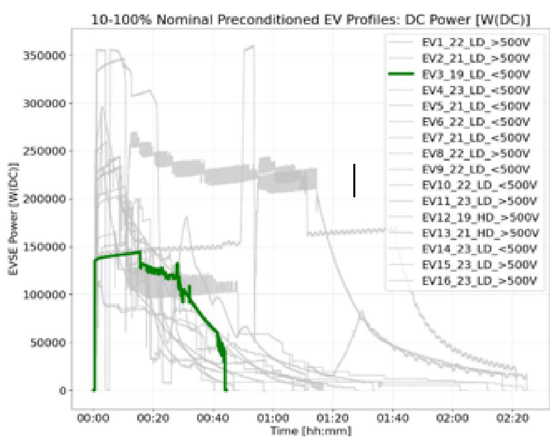
Vehicle Description	
Identifier	EV3
Model Year	2019
Vehicle Type	Light Duty
Nominal Charging Voltage	< 500VDC
Rated Usable Energy	50-100 kWh
Rated Max Charge Power	100-150 kW
Rated Charge Time (10-80%)	~30 min
Rated Range	250-300 miles
EVSE Charged On	EVSE1_H1

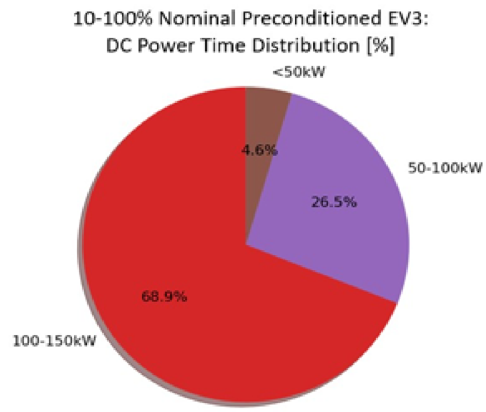
SOC, kWh, Range





DC Power



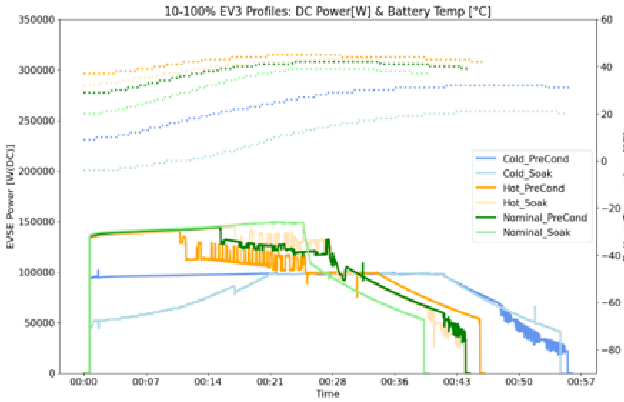


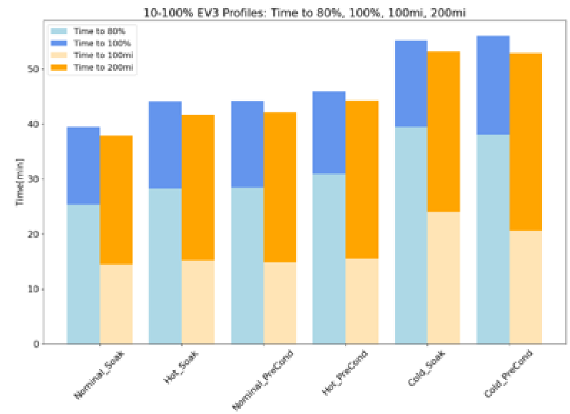
Testing Conditions	SOC: 10-80%				SOC: 10-100%						
	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	I_{peak} [A]	P_{peak} [kW]	Battery $Temp_{peak}$
Nominal PreCond	0:28	311	130	62	0:44	261	111	82	~350	~150	42°C
Nominal Soak	0:25	334	140	59	0:39	279	119	78	~350	~150	39°C
Hot PreCond	0:31	281	117	60	46	246	104	80	~350	~150	45°C
Hot Soak	0:28	315	132	62	0:44	262	112	82	~350	~150	43°C
Cold PreCond	0:38	229	96	61	0:56	202	86	81	~250	~100	32°C
Cold Soak	0:39	193	81	53	0:55	183	78	72	~250	~100	21°C

EV3_19_LD_<500V

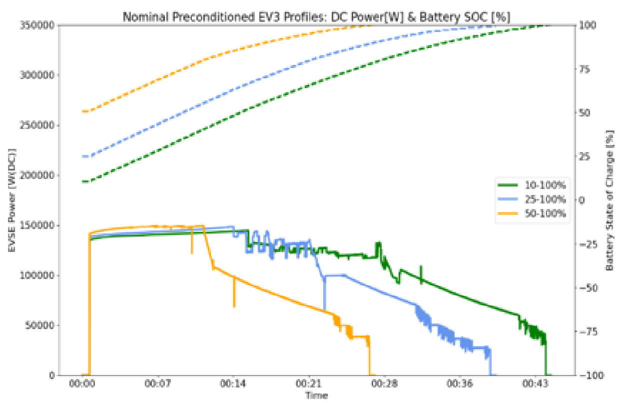
Page (2/2)

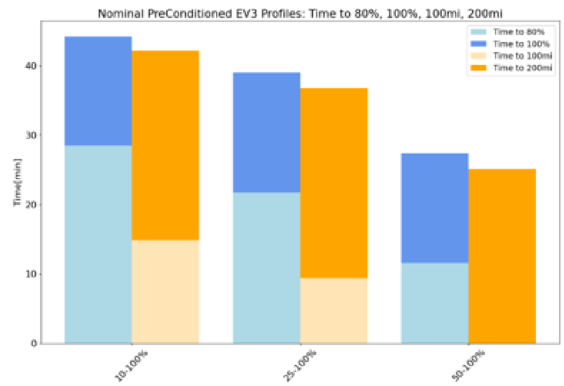
Temperature & Conditioning Variance



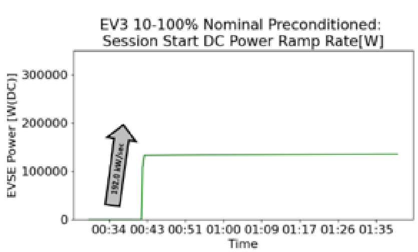


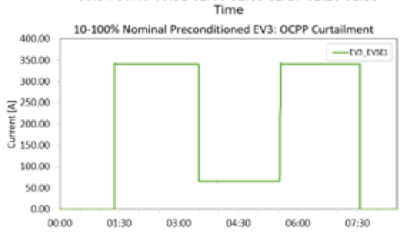
Start SOC Variance



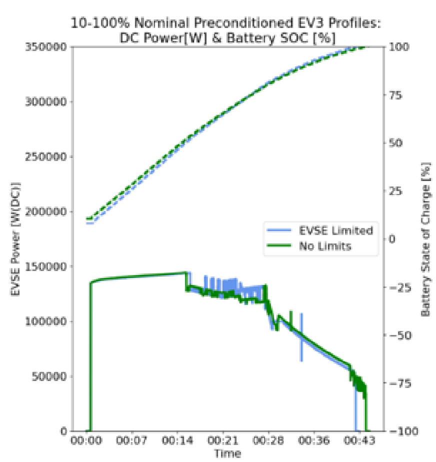


Ramp Rate & SCM





EVSE Limited



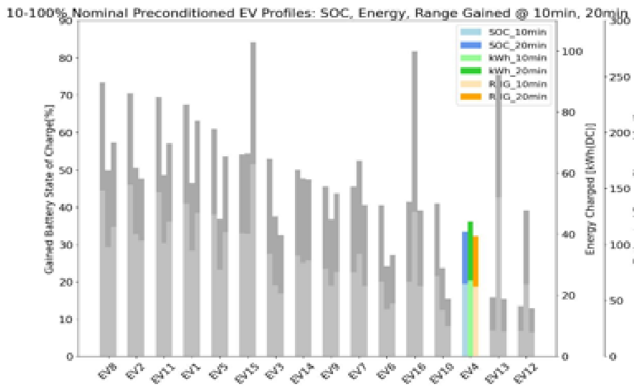
Adapters/Converters

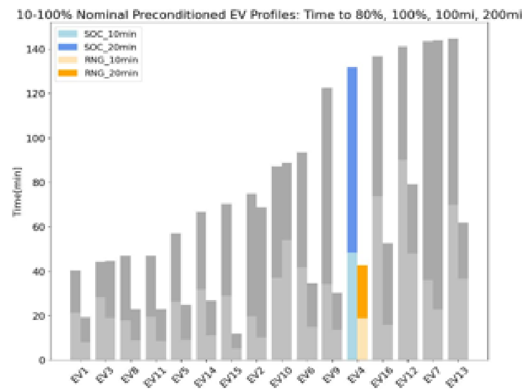
EV4_23_LD_<500V

Page (1/2)

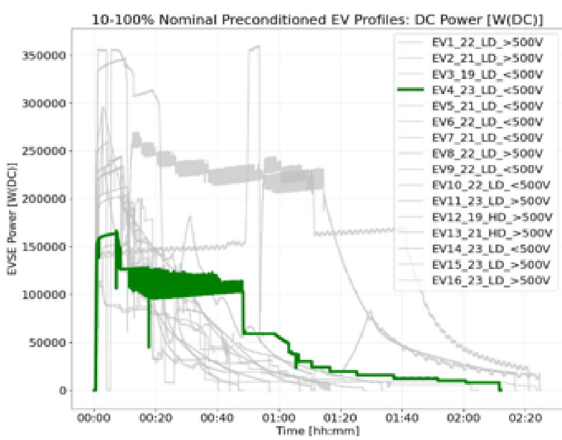
Vehicle Description	
Identifier	EV4
Model Year	2023
Vehicle Type	Light Duty
Nominal Charging Voltage	< 500VDC
Rated Usable Energy	100-150 kWh
Rated Max Charge Power	150-200 kW
Rated Charge Time (10-80%)	~40 min
Rated Range	300-350 miles
EVSE Charged On	EVSE1_H1

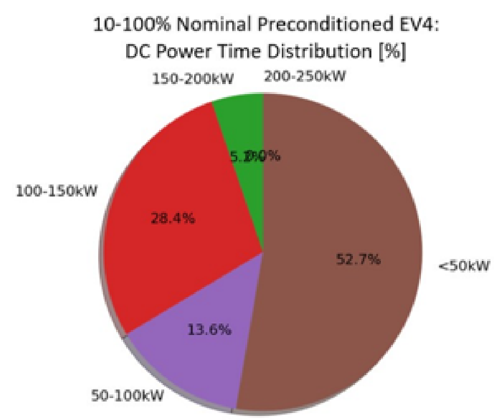
SOC, kWh, Range





DC Power



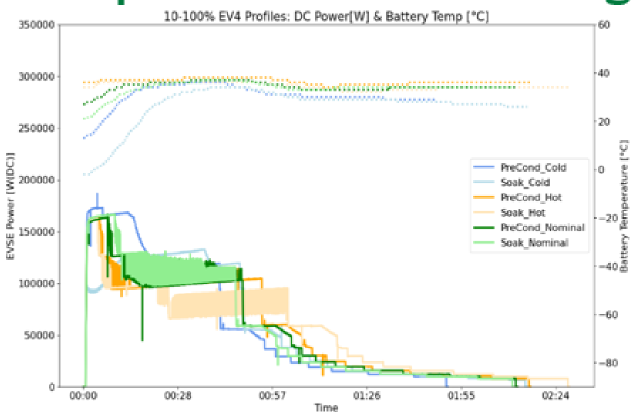


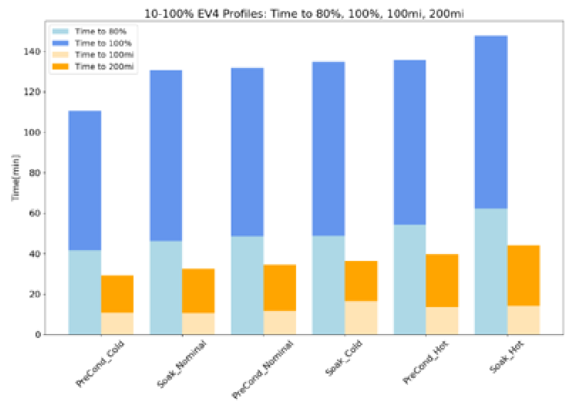
Testing Conditions	SOC: 10-80%				SOC: 10-100%						
	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	I_{peak} [A]	P_{peak} [kW]	Battery $Temp_{peak}$
Nominal PreCond	0:49	315	116	94	2:12	154	58	127	~450	~150	37°C
Nominal Soak	0:46	326	121	94	2:11	151	57	124	~450	~150	37°C
Hot PreCond	0:54	285	105	95	2:16	148	55	125	~450	~150	38°C
Hot Soak	1:02	249	91	94	2:28	139	52	127	~450	~150	36°C
Cold PreCond	0:42	363	136	95	1:50	177	67	123	~500	~200	36°C
Cold Soak	0:49	315	118	96	2:14	147	56	125	~350	~150	34°C

EV4_23_LD_<500V

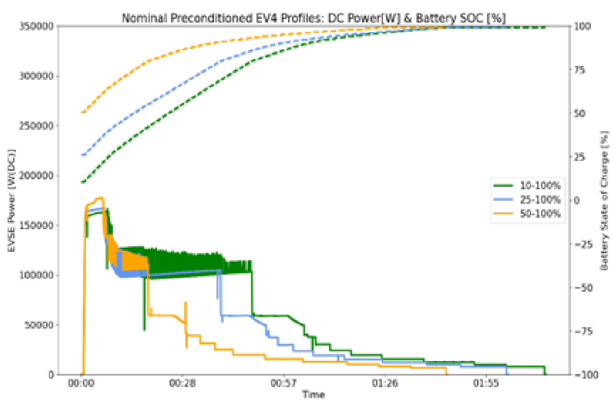
Page (2/2)

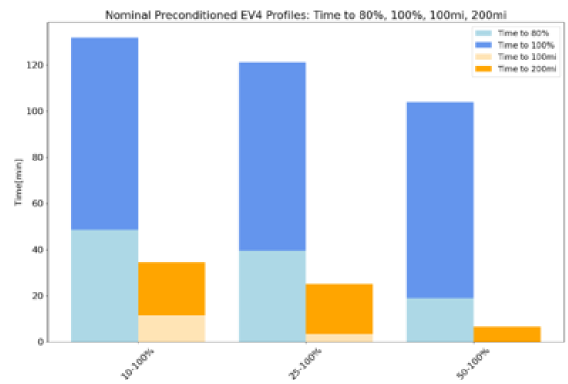
Temperature & Conditioning Variance



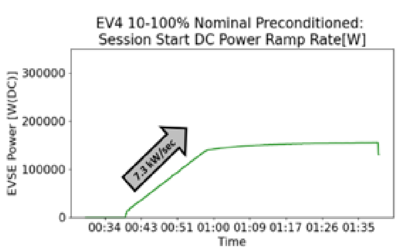


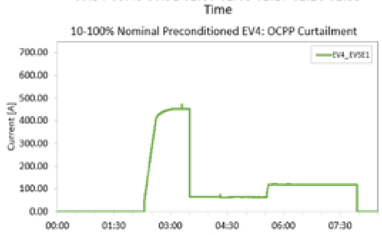
Start SOC Variance



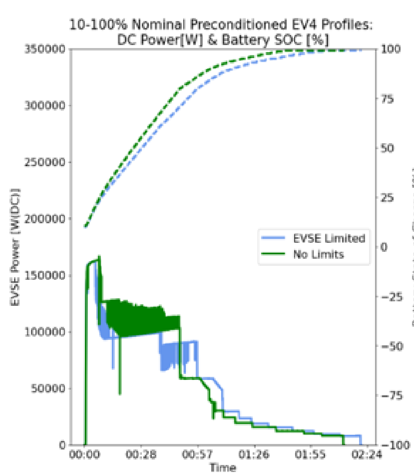


Ramp Rate & SCM

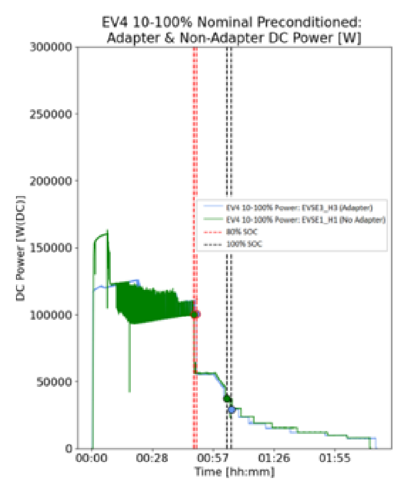




EVSE Limited



Adapters/Converters

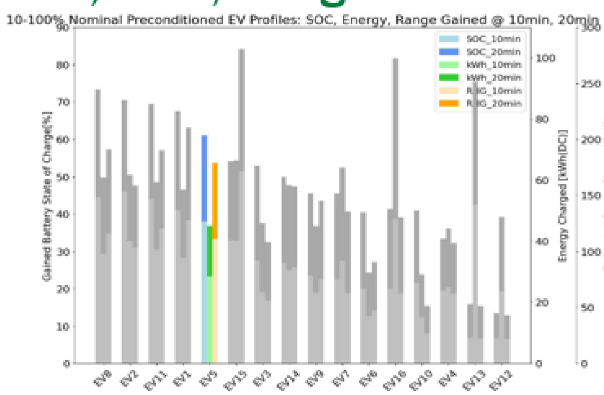


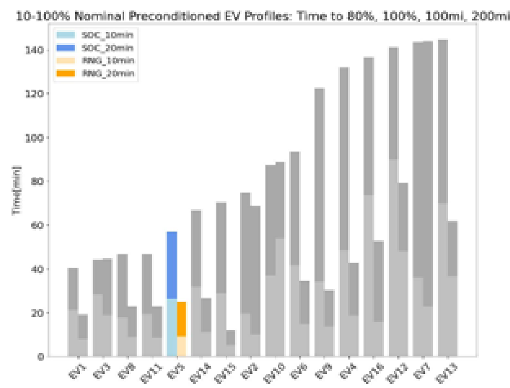
EV5_21_LD_<500V

Page (1/2)

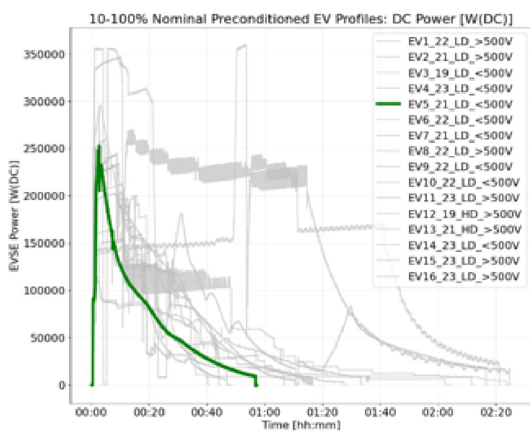
Vehicle Description	
Identifier	EV5
Model Year	2021
Vehicle Type	Light Duty
Nominal Charging Voltage	< 500VDC
Rated Usable Energy	50-100 kWh
Rated Max Charge Power	200-250 kW
Rated Charge Time (10-80%)	~30 min
Rated Range	250-300 miles
EVSE Charged On	EVSE3_H3

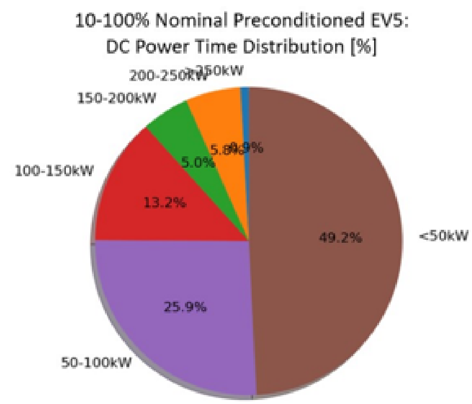
SOC, kWh, Range





DC Power



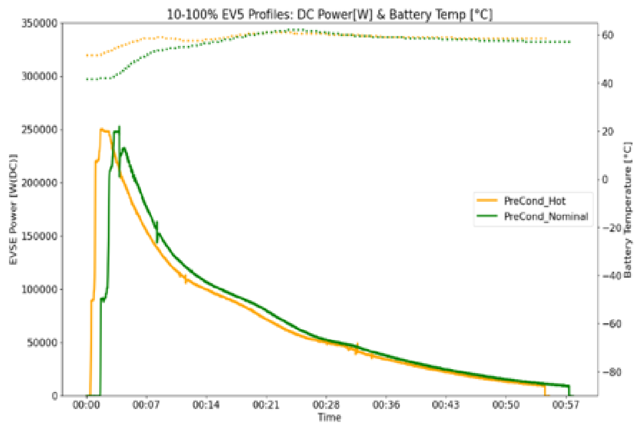


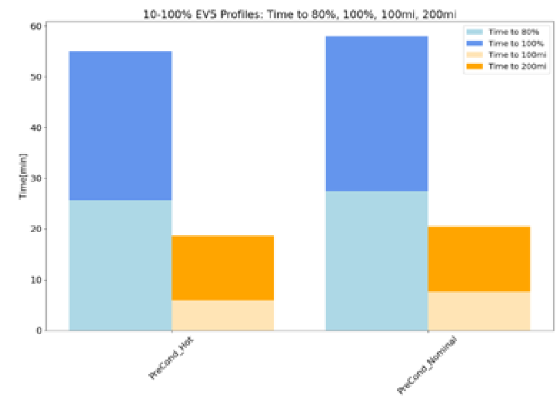
Testing Conditions	SOC: 10-80%				SOC: 10-100%						
	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	I_{peak} [A]	P_{peak} [kW]	Battery $Temp_{peak}$
Nominal PreCond	0:27	293	113	58	0:58	175	68	74	~650	~250	62°C
Nominal Soak	X	X	X	X	X	X	X	X	X	X	X
Hot PreCond	0:26	310	119	57	0:55	183	71	73	~650	~250	61°C
Hot Soak	X	X	X	X	X	X	X	X	X	X	X
Cold PreCond	X	X	X	X	X	X	X	X	X	X	X
Cold Soak	X	X	X	X	X	X	X	X	X	X	X

EV5_21_LD_<500V

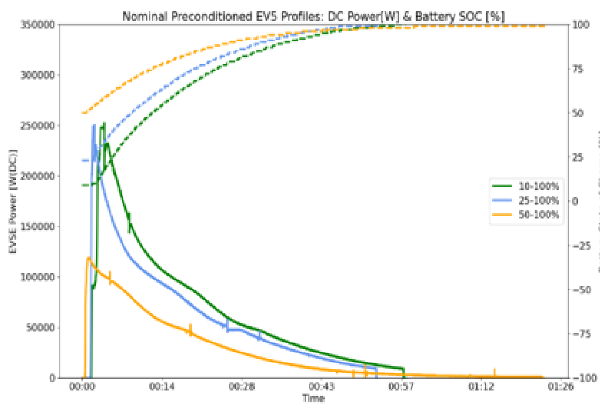
Page (2/2)

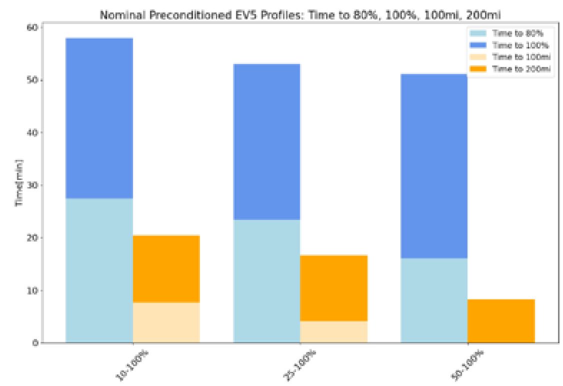
Temperature & Conditioning Variance



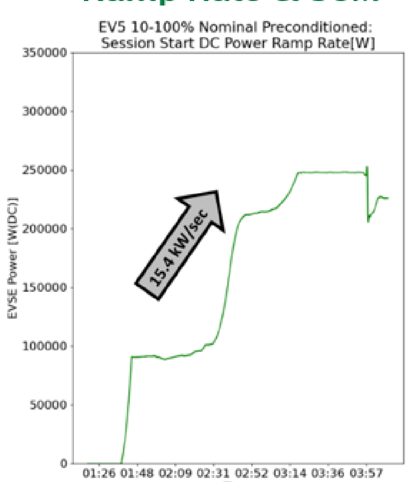


Start SOC Variance

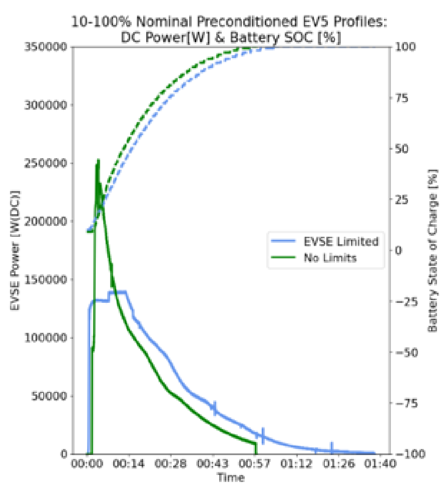




Ramp Rate & SCM



EVSE Limited



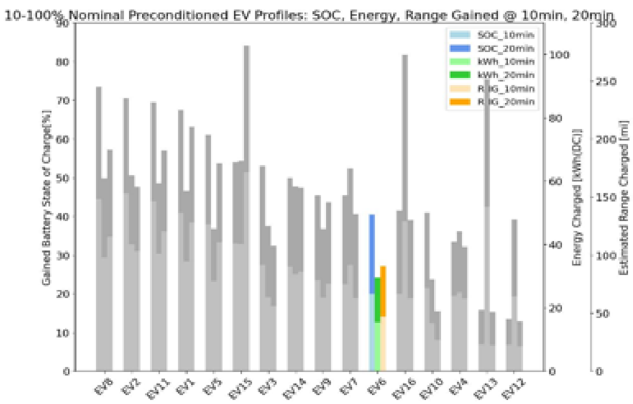
Adapters/Converters

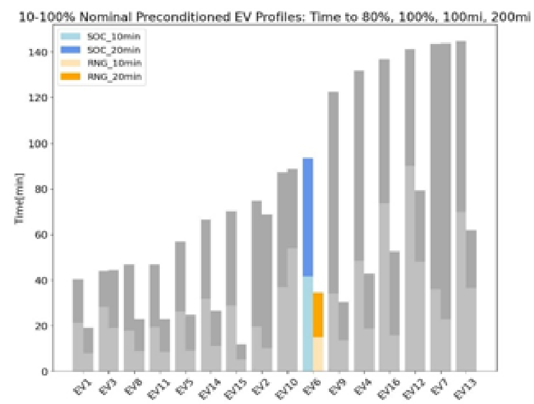
EV6_21_LD_<500V

Page (1/2)

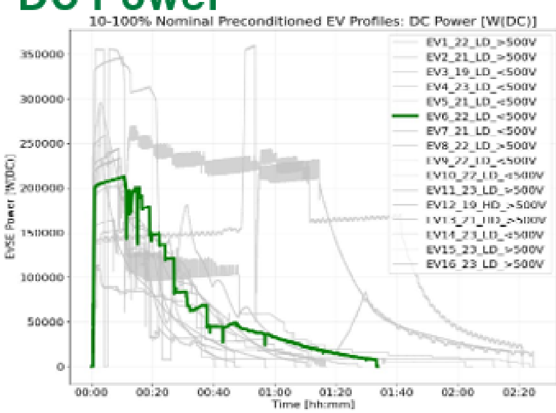
Vehicle Description	
Identifier	EV6
Model Year	2021
Vehicle Type	Light Duty
Nominal Charging Voltage	< 500VDC
Rated Usable Energy	100-150 kWh
Rated Max Charge Power	200-250 kW
Rated Charge Time (10-80%)	~40 min
Rated Range	250-300 miles
EVSE Charged On	EVSE1_H1

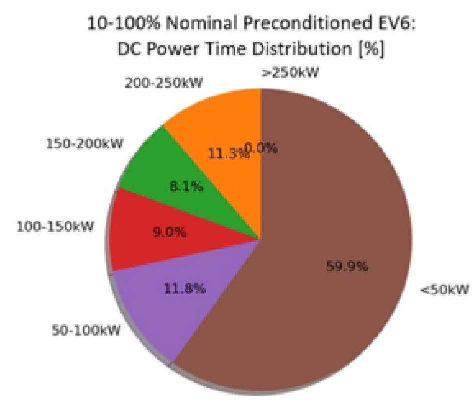
SOC, kWh, Range





DC Power



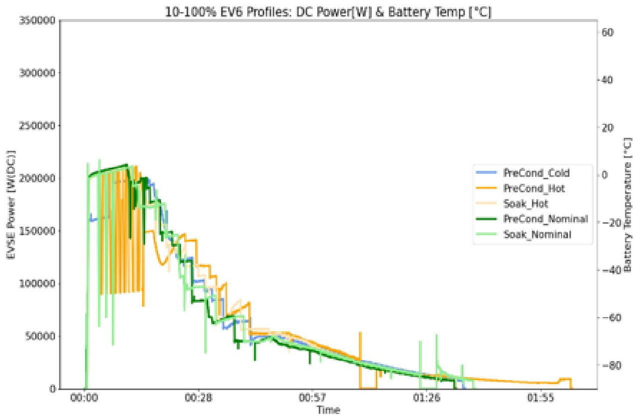


Testing Conditions	SOC: 10-80%				SOC: 10-100%						
	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	I_{peak} [A]	P_{peak} [kW]	Battery $Temp_{peak}$
Nominal PreCond	X	X	X	X	1:33	173	75	117	~500	~200	X
Nominal Soak	X	X	X	X	1:25	195	85	115	~550	~200	X
Hot PreCond	X	X	X	X	1:09	222	96	111	~500	~200	X
Hot Soak	X	X	X	X	1:34	181	79	123	~500	~200	X
Cold PreCond	X	X	X	X	1:35	96	75	120	~500	~200	X
Cold Soak	X	X	X	X	X	X	X	X	X	X	X

EV6_21_LD_<500V

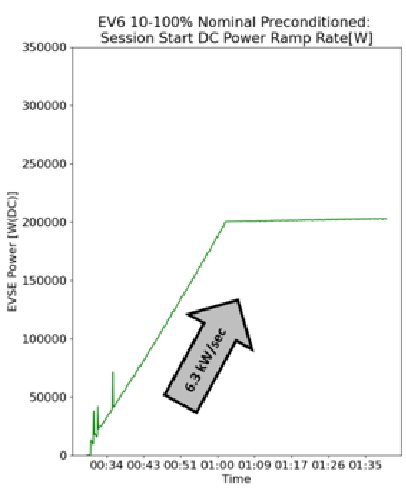
Page (2/2)

Temperature & Conditioning Variance



Start SOC Variance

Ramp Rate & SCM



EVSE Limited

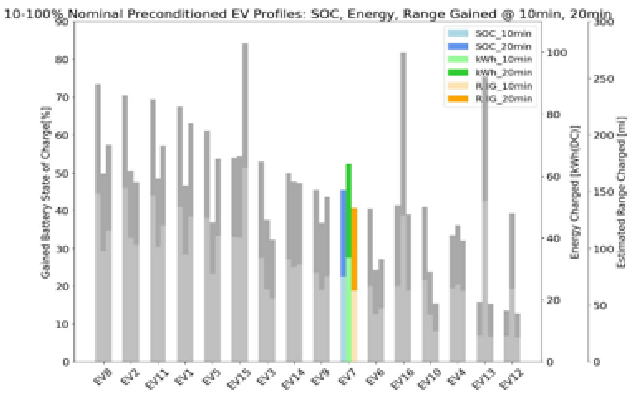
Adapters/Converters

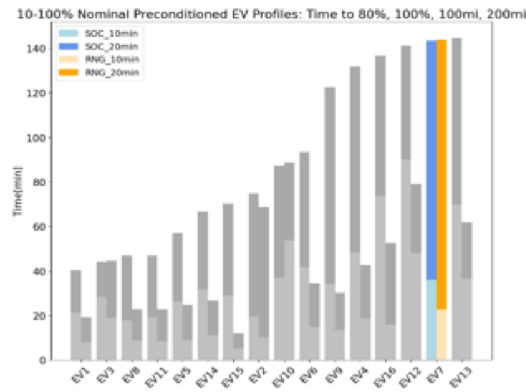
EV7_21_LD_<500V

Page (1/2)

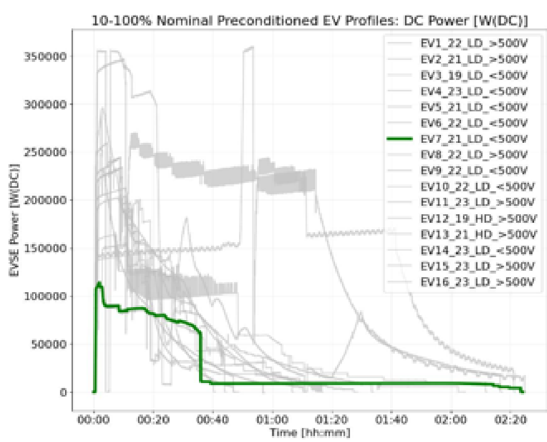
Vehicle Description	
Identifier	EV7
Model Year	2021
Vehicle Type	Light Duty
Nominal Charging Voltage	< 500VDC
Rated Usable Energy	50-100 kWh
Rated Max Charge Power	100-150 kW
Rated Charge Time (10-80%)	~40 min
Rated Range	150-200 miles
EVSE Charged On	EVSE2_H1

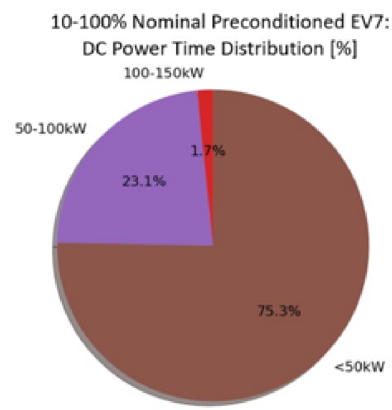
SOC, kWh, Range





DC Power



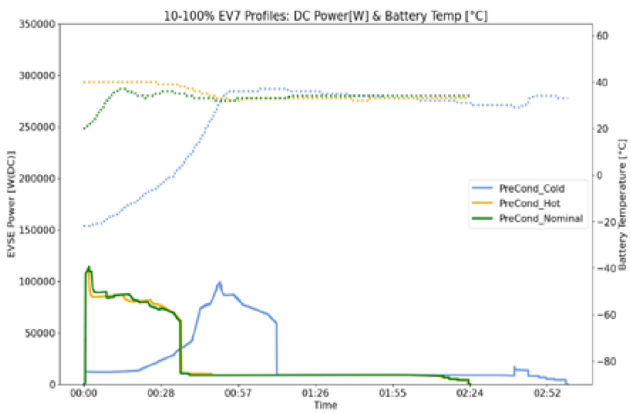


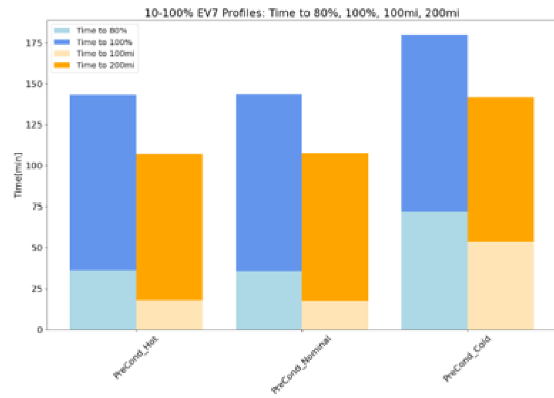
Testing Conditions	SOC: 10-80%				SOC: 10-100%						
	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	I_{peak} [A]	P_{peak} [kW]	Battery $Temp_{peak}$
Nominal PreCond	0:36	218	81	49	2:23	71	27	64	~300	~100	37°C
Nominal Soak	X	X	X	X	X	X	X	X	X	X	X
Hot PreCond	0:36	215	80	48	1:23	71	27	64	~300	~100	40°C
Hot Soak	X	X	X	X	X	X	X	X	X	X	X
Cold PreCond	1:12	119	44	53	2:59	61	23	69	~300	~100	37°C
Cold Soak	X	X	X	X	X	X	X	X	X	X	X

EV7_21_LD_<500V

Page (2/2)

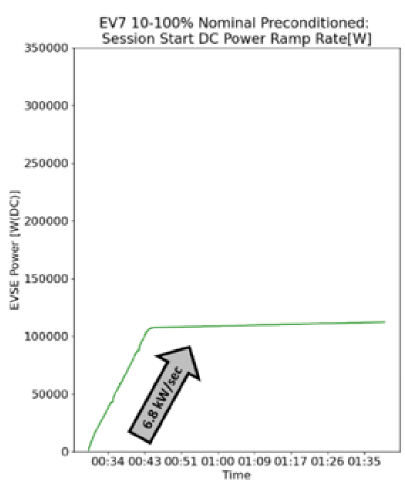
Temperature & Conditioning Variance





Start SOC Variance

Ramp Rate & SCM



EVSE Limited

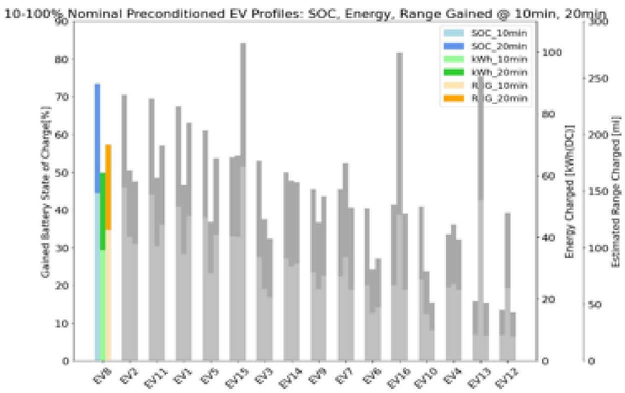
Adapters/Converters

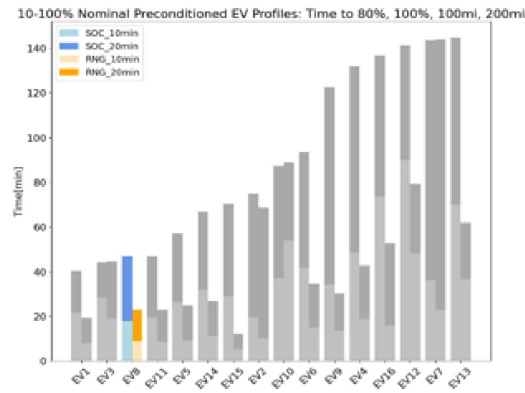
EV8_22_LD_>500V

Page (1/2)

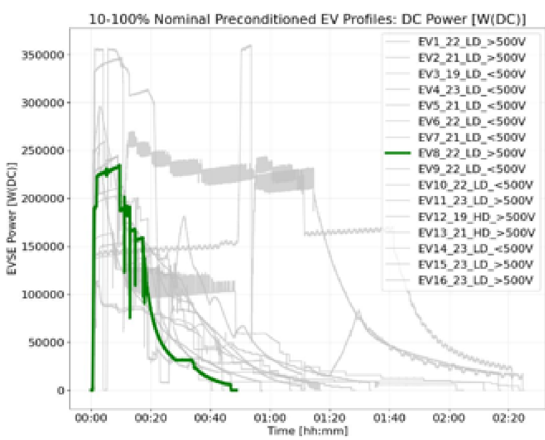
Vehicle Description	
Identifier	EV8
Model Year	2022
Vehicle Type	Light Duty
Nominal Charging Voltage	> 500VDC
Rated Usable Energy	50-100 kWh
Rated Max Charge Power	200-250 kW
Rated Charge Time (10-80%)	~20 min
Rated Range	250-300 miles
EVSE Charged On	EVSE2_H1

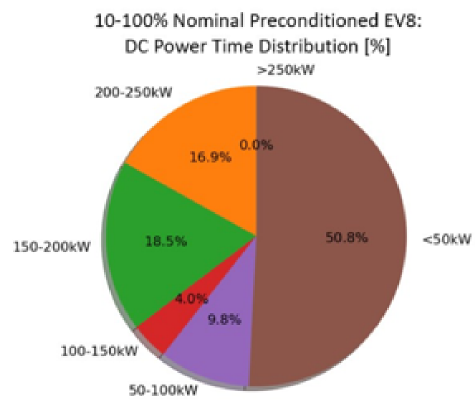
SOC, kWh, Range





DC Power



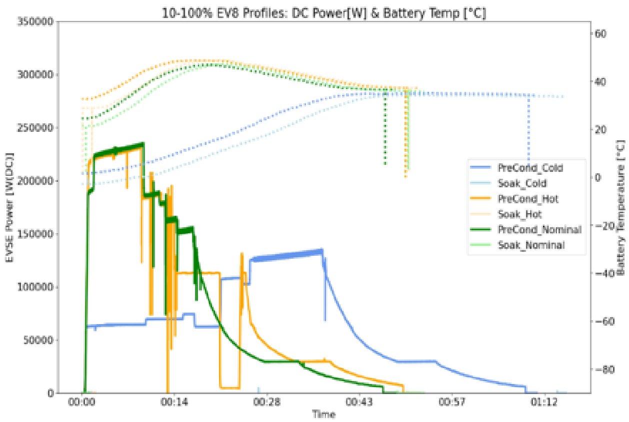


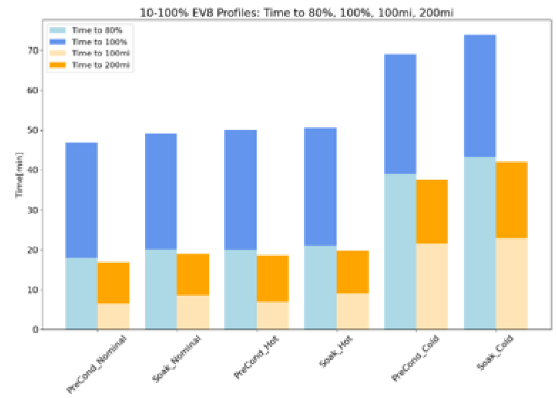
Testing Conditions	SOC: 10-80%				SOC: 10-100%						
	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	I_{peak} [A]	P_{peak} [kW]	Battery $Temp_{peak}$
Nominal PreCond	0:18	249	190	57	0:47	122	93	73	~300	~250	47°C
Nominal Soak	0:20	234	179	60	0:49	121	93	76	~300	~250	47°C
Hot PreCond	0:20	240	181	60	0:50	123	94	78	~300	~250	49°C
Hot Soak	0:21	235	178	62	0:51	124	95	80	~300	~250	49°C
Cold PreCond	0:39	123	92	60	1:09	86	65	75	~150	~150	35°C
Cold Soak	0:43	112	84	60	1:14	81	61	76	~200	~150	34°C

EV8_22_LD_>500V

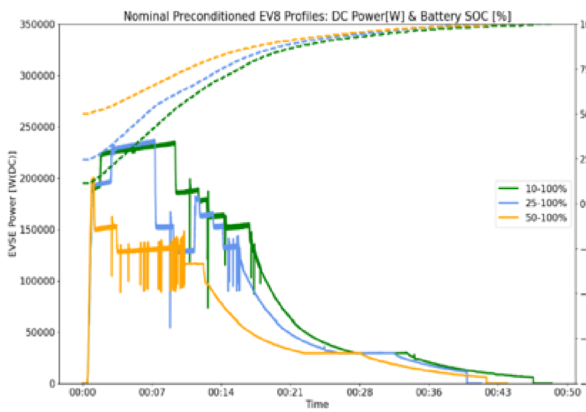
Page (2/2)

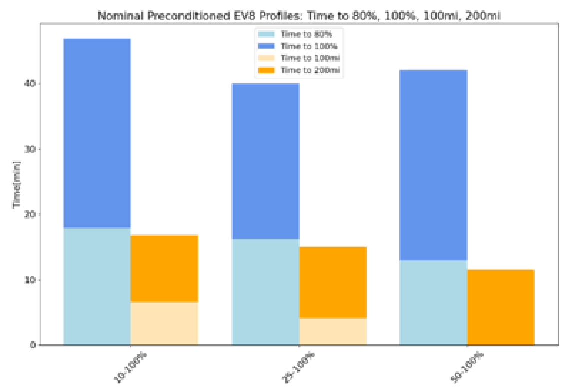
Temperature & Conditioning Variance



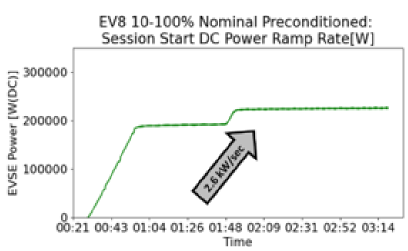


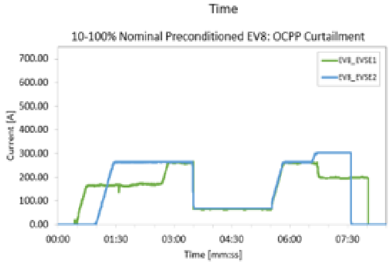
Start SOC Variance



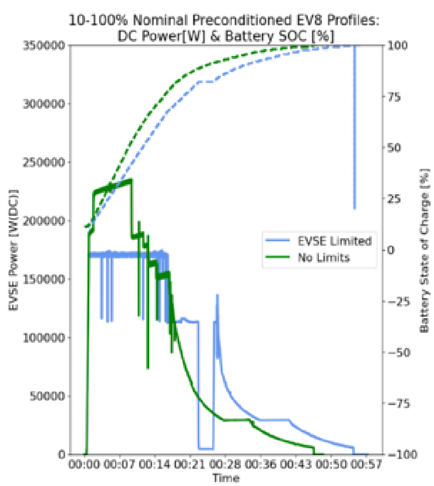


Ramp Rate & SCM





EVSE Limited



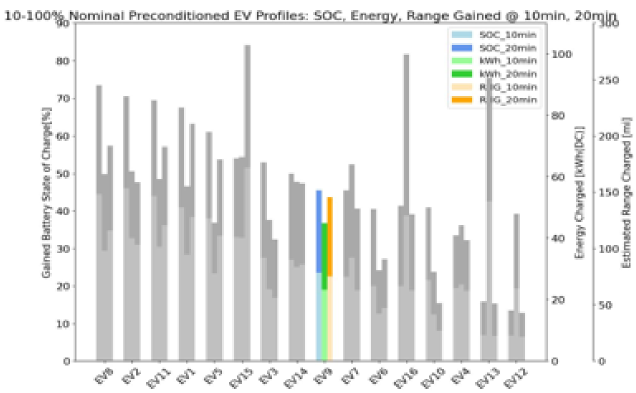
Adapters/Converters

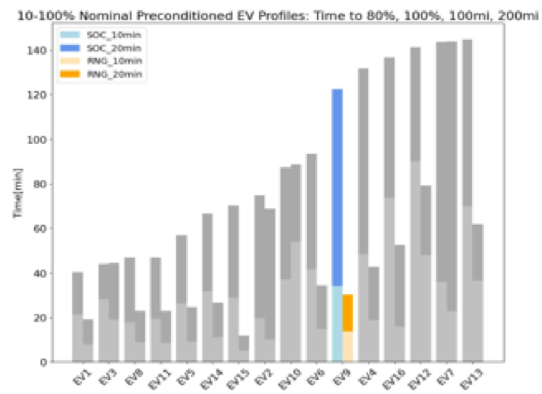
EV9_22_LD_<500V

Page (1/2)

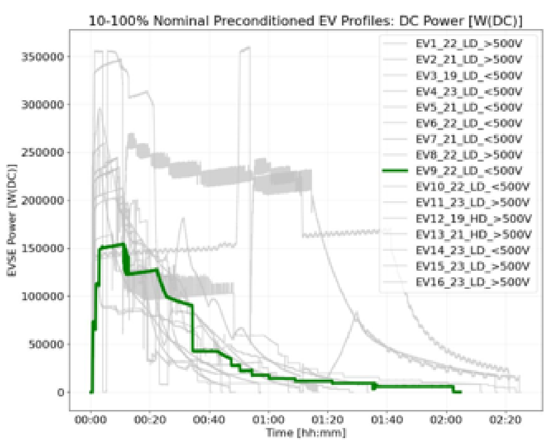
Vehicle Description	
Identifier	EV9
Model Year	2022
Vehicle Type	Light Duty
Nominal Charging Voltage	< 500VDC
Rated Usable Energy	100-150 kWh
Rated Max Charge Power	150-200 kW
Rated Charge Time (10-80%)	~30 min
Rated Range	300-350 miles
EVSE Charged On	EVSE1_H1

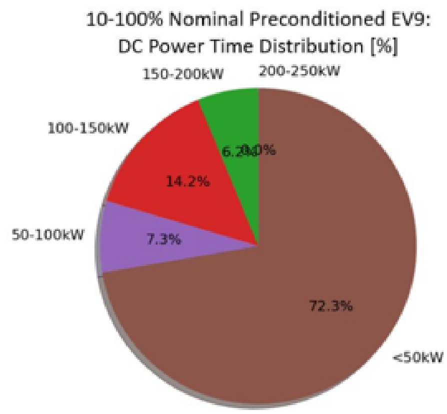
SOC, kWh, Range





DC Power



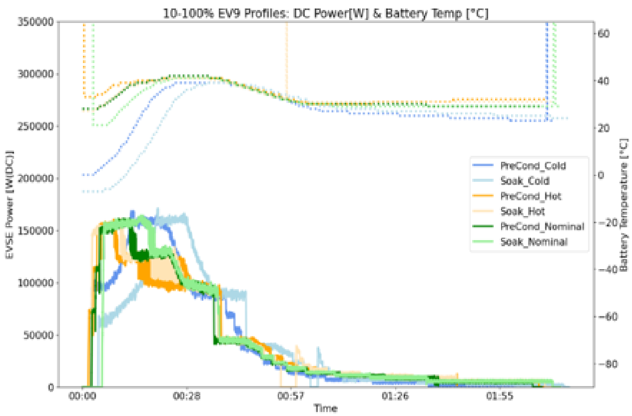


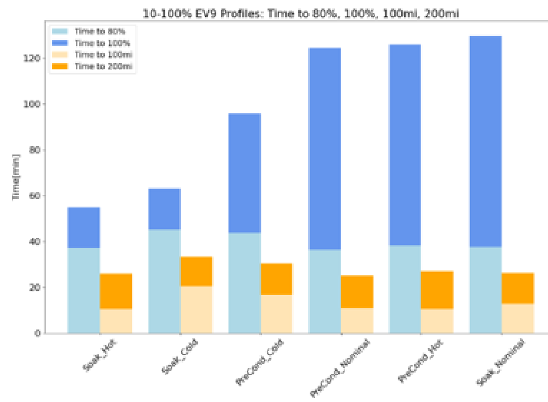
Testing Conditions	SOC: 10-80%				SOC: 10-100%						
	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	I_{peak} [A]	P_{peak} [kW]	Battery $Temp_{peak}$
Nominal PreCond	0:36	328	114	69	2:04	125	44	91	~450	~150	42°C
Nominal Soak	0:38	312	110	69	2:10	119	42	91	~450	~150	42°C
Hot PreCond	0:38	316	109	69	2:06	126	44	93	~450	~150	44°C
Hot Soak	0:37	327	113	70	0:54	256	89	82	~450	~150	41°C
Cold PreCond	0:44	302	108	79	1:35	157	56	90	~500	~200	39°C
Cold Soak	0:45	276	99	74	1:02	223	80	84	~500	~200	39°C

EV9_22_LD_<500V

Page (2/2)

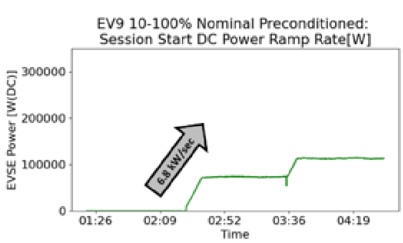
Temperature & Conditioning Variance

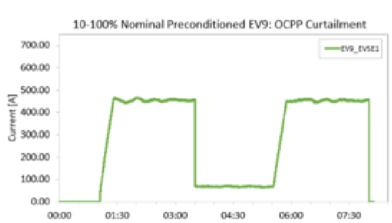




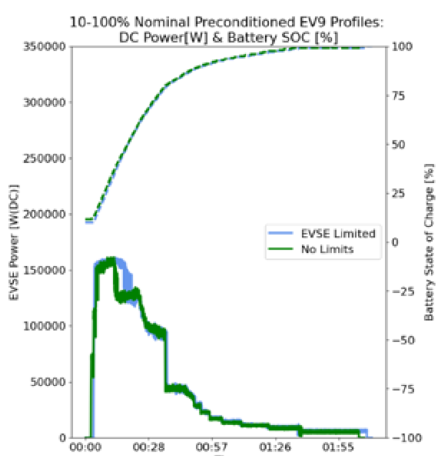
Start SOC Variance

Ramp Rate & SCM





EVSE Limited



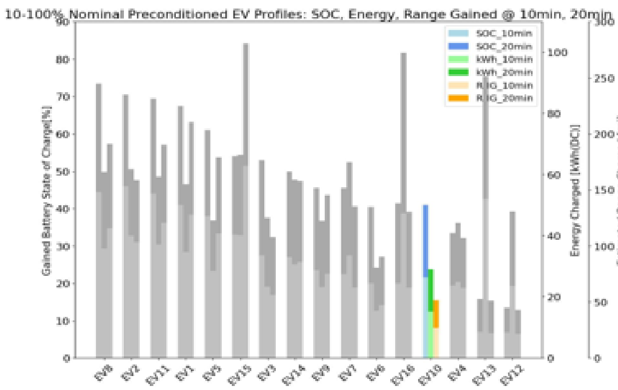
Adapters/Converters

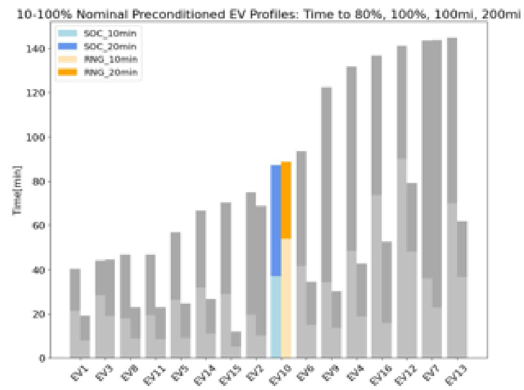
EV10_22_LD_<500V

Page (1/2)

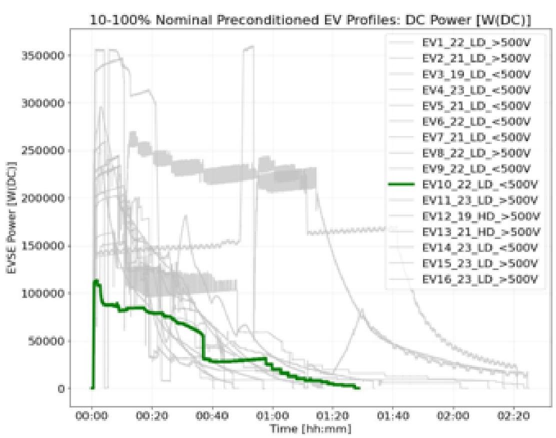
Vehicle Description	
Identifier	EV10
Model Year	2022
Vehicle Type	Light Duty
Nominal Charging Voltage	< 500VDC
Rated Usable Energy	50-100 kWh
Rated Max Charge Power	100-150 kW
Rated Charge Time (10-80%)	~40 min
Rated Range	100-150 miles
EVSE Charged On	EVSE2_H1

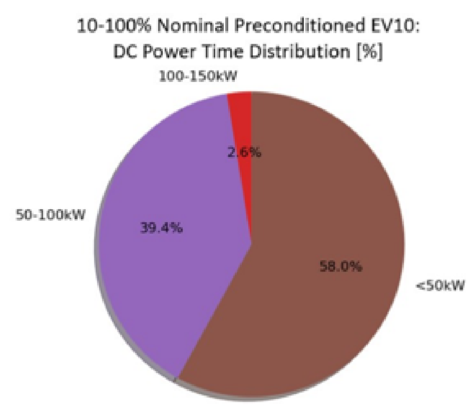
SOC, kWh, Range





DC Power



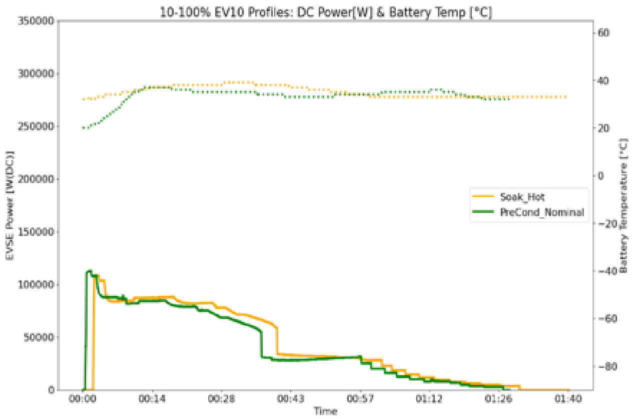


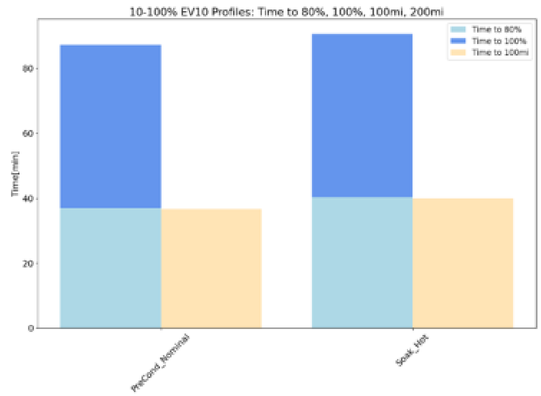
Testing Conditions	SOC: 10-80%				SOC: 10-100%						
	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	I_{peak} [A]	P_{peak} [kW]	Battery $Temp_{peak}$
Nominal PreCond	0:40	208	77	52	1:31	120	45	68	~300	~100	39°C
Nominal Soak	X	X	X	X	X	X	X	X	X	X	X
Hot PreCond	X	X	X	X	X	X	X	X	X	X	X
Hot Soak	0:37	211	78	48	1:27	116	44	63	~300	~100	37°C
Cold PreCond	X	X	X	X	X	X	X	X	X	X	X
Cold Soak	X	X	X	X	X	X	X	X	X	X	X

EV10_22_LD_<500V

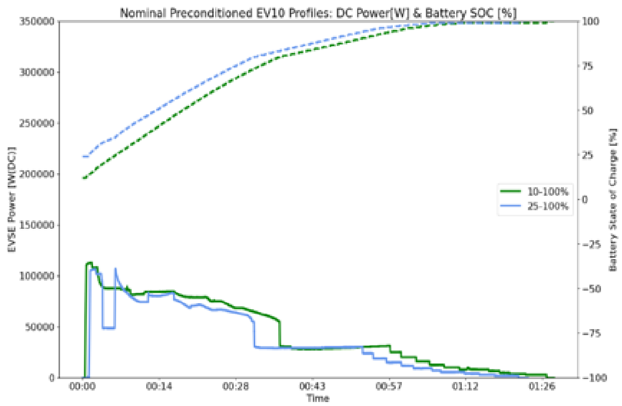
Page (2/2)

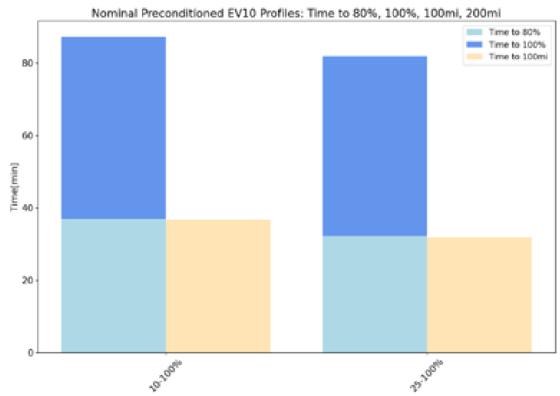
Temperature & Conditioning Variance



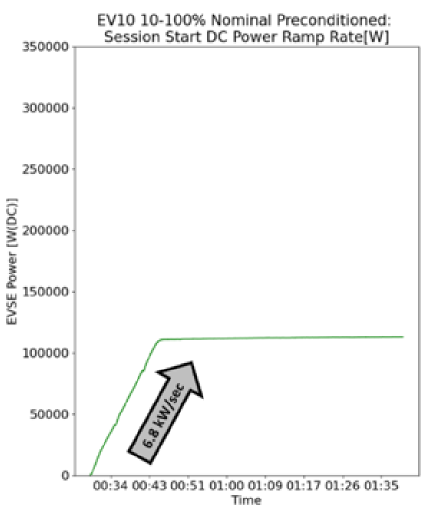


Start SOC Variance





Ramp Rate & SCM



EVSE Limited

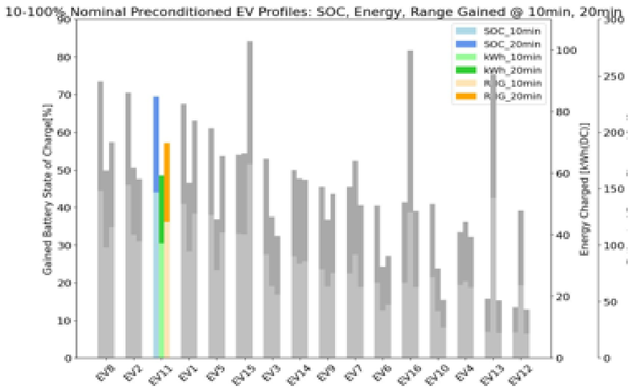
Adapters/Converters

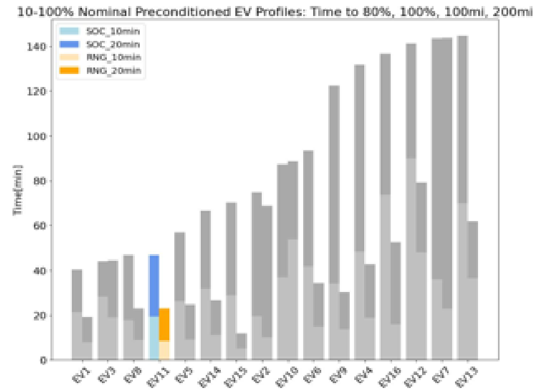
EV11_23_LD_>500V

Page (1/2)

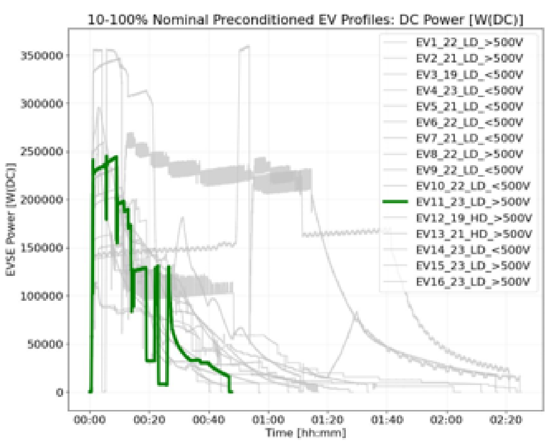
Vehicle Description	
Identifier	EV11
Model Year	2023
Vehicle Type	Light Duty
Nominal Charging Voltage	> 500VDC
Rated Usable Energy	50-100 kWh
Rated Max Charge Power	200-250 kW
Rated Charge Time (10-80%)	~20 min
Rated Range	250-300 miles
EVSE Charged On	EVSE2_H1

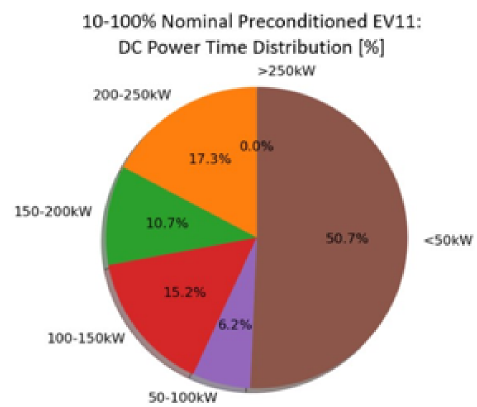
SOC, kWh, Range





DC Power





Testing Conditions	SOC: 10-80%				SOC: 10-100%						
	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	I_{peak} [A]	P_{peak} [kW]	Battery $Temp_{peak}$
Nominal PreCond	0:19	238	181	59	0:47	127	97	76	~350	~250	49°C
Nominal Soak	X	X	X	X	X	X	X	X	X	X	X
Hot PreCond	X	X	X	X	X	X	X	X	X	X	X
Hot Soak	X	X	X	X	X	X	X	X	X	X	X
Cold PreCond	X	X	X	X	X	X	X	X	X	X	X
Cold Soak	X	X	X	X	X	X	X	X	X	X	X

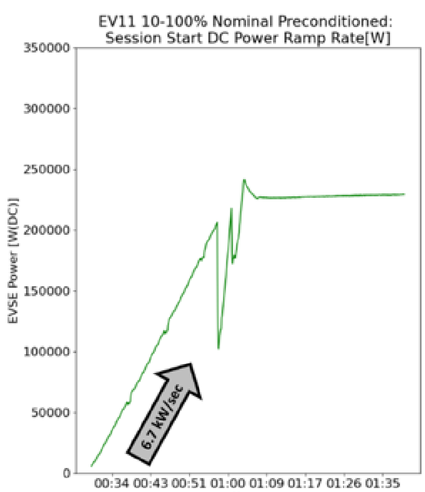
EV11_23_LD_>500V

Page (2/2)

Temperature & Conditioning Variance

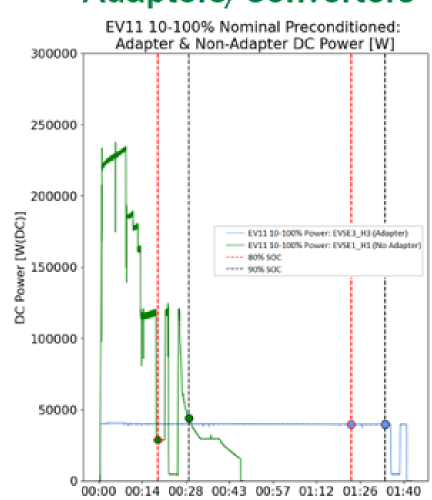
Start SOC Variance

Ramp Rate & SCM



EVSE Limited

Adapters/Converters

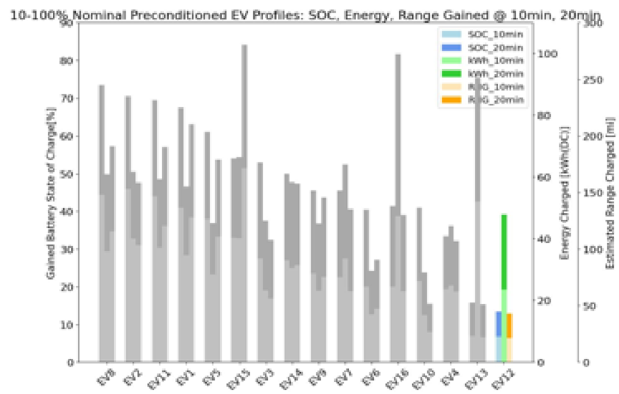


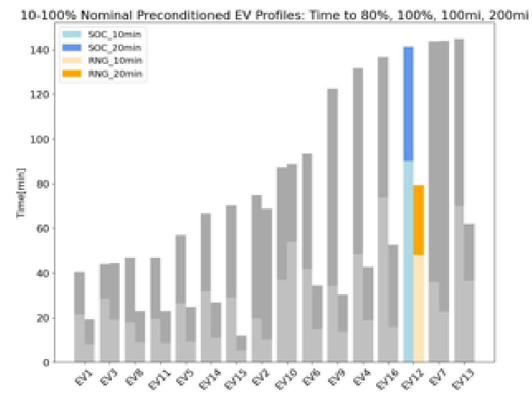
EV12_19_HD_>500V

Page (1/2)

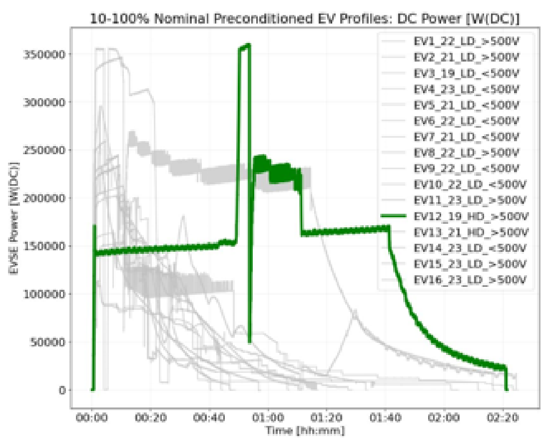
Vehicle Description	
Identifier	EV12
Model Year	2019
Vehicle Type	Heavy Duty
Nominal Charging Voltage	> 500VDC
Rated Usable Energy	300-350 kWh
Rated Max Charge Power	350-400 kW
Rated Charge Time (10-80%)	~ 80min
Rated Range	250-300 miles
EVSE Charged On	EVSE4_H5

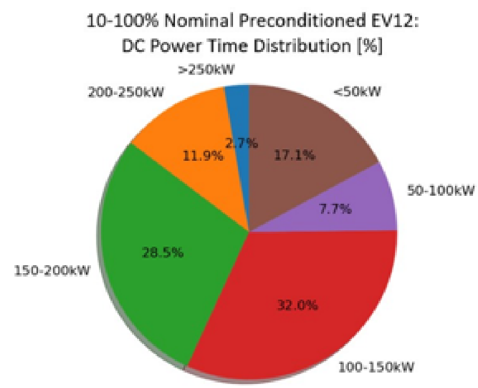
SOC, kWh, Range





DC Power



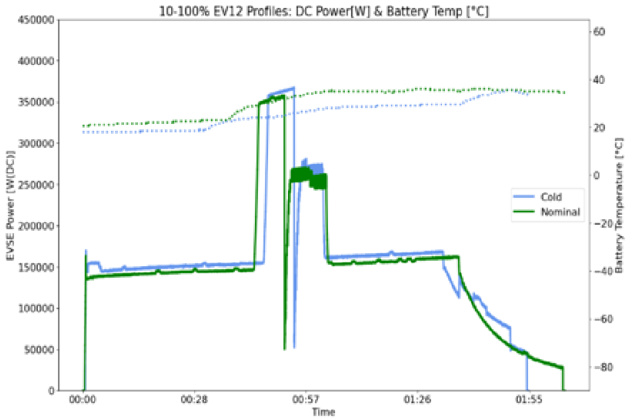


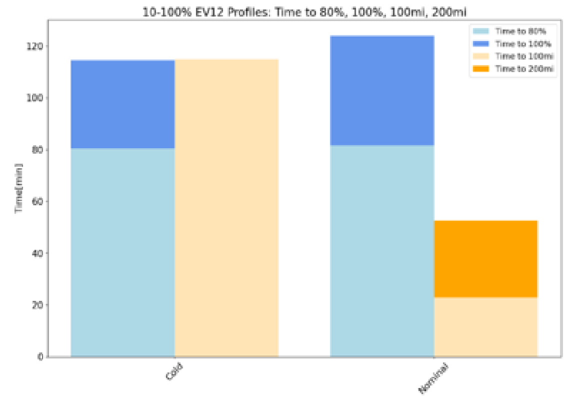
Testing Conditions	SOC: 10-80%				SOC: 10-100%						
	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	I_{peak} [A]	P_{peak} [kW]	Battery $Temp_{peak}$
Nominal PreCond	1:22	257	177	235	2:03	215	150	303	~500	~350	X
Nominal Soak	X	X	X	X	X	X	X	X	X	X	X
Hot PreCond	X	X	X	X	X	X	X	X	X	X	X
Hot Soak	X	X	X	X	X	X	X	X	X	X	X
Cold PreCond	1:20	261	180	228	1:54	233	163	287	~500	~350	X
Cold Soak	X	X	X	X	X	X	X	X	X	X	X

EV12_19_HD_>500V

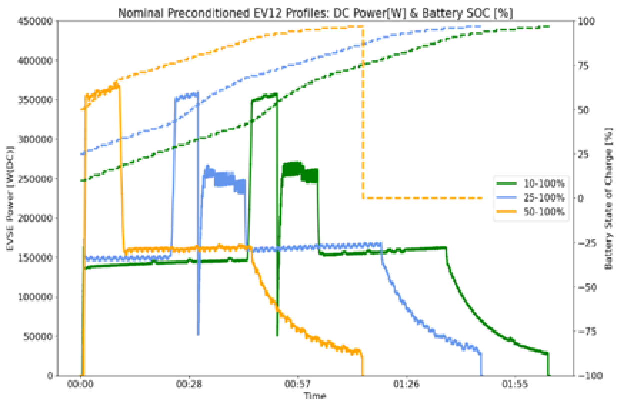
Page (2/2)

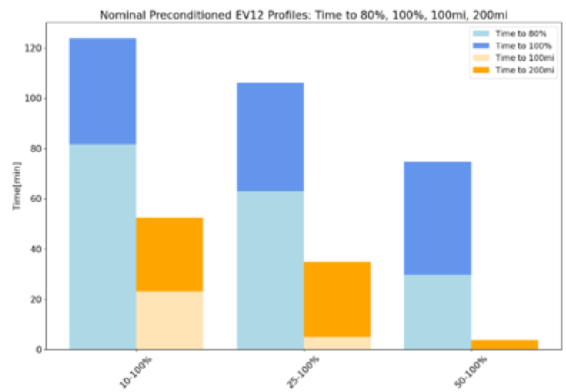
Temperature & Conditioning Variance



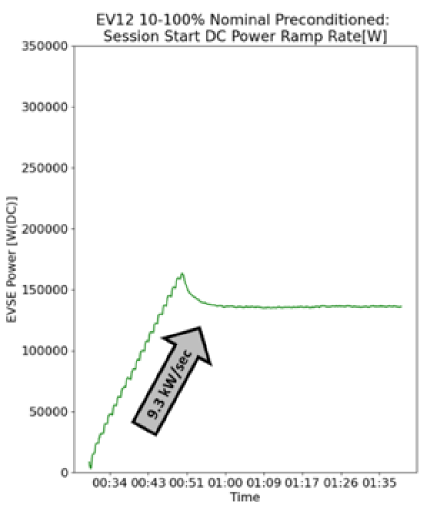


Start SOC Variance





Ramp Rate & SCM



EVSE Limited

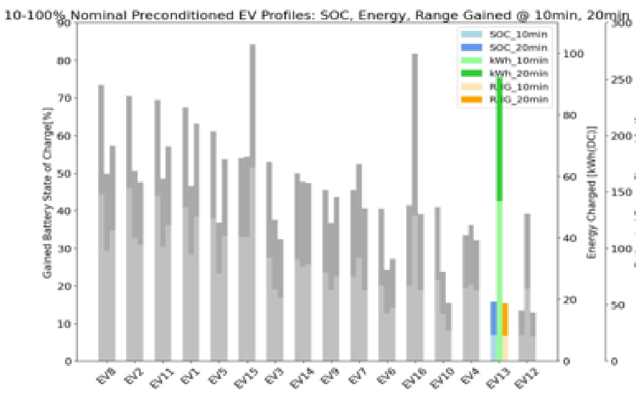
Adapters/Converters

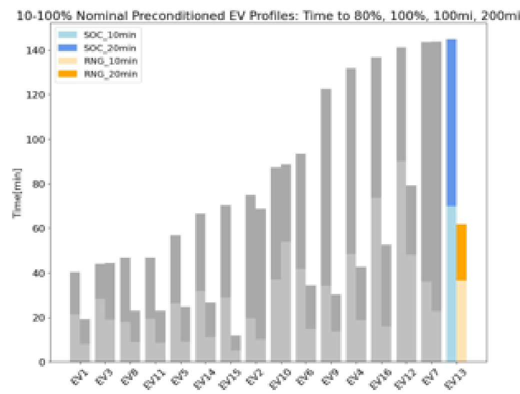
EV13_21_HD_>500V

Page (1/2)

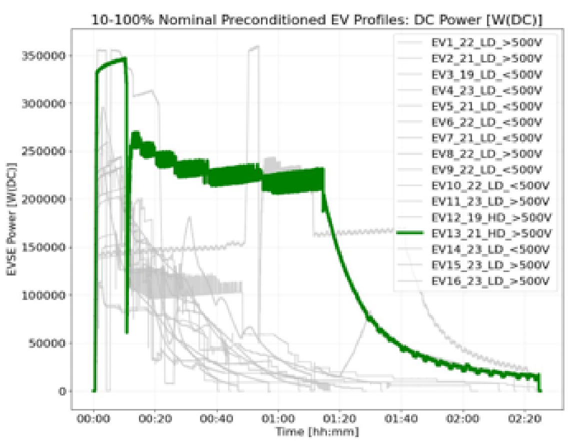
Vehicle Description	
Identifier	EV13
Model Year	2021
Vehicle Type	Heavy Duty
Nominal Charging Voltage	> 500VDC
Rated Usable Energy	300-350 kWh
Rated Max Charge Power	350-400 kW
Rated Charge Time (10-80%)	~ 80min
Rated Range	250-300 miles
EVSE Charged On	EVSE4_H5

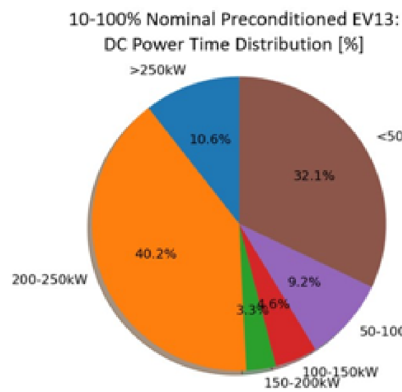
SOC, kWh, Range





DC Power



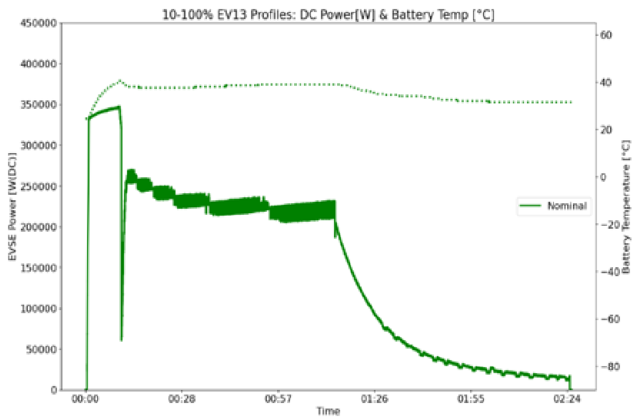


Testing Conditions	SOC: 10-80%				SOC: 10-100%						
	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	I_{peak} [A]	P_{peak} [kW]	Battery $Temp_{peak}$
Nominal PreCond	1:09	349	242	272	2:24	213	150	347	~500	~350	X
Nominal Soak	X	X	X	X	X	X	X	X	X	X	X
Hot PreCond	X	X	X	X	X	X	X	X	X	X	X
Hot Soak	X	X	X	X	X	X	X	X	X	X	X
Cold PreCond	X	X	X	X	X	X	X	X	X	X	X
Cold Soak	X	X	X	X	X	X	X	X	X	X	X

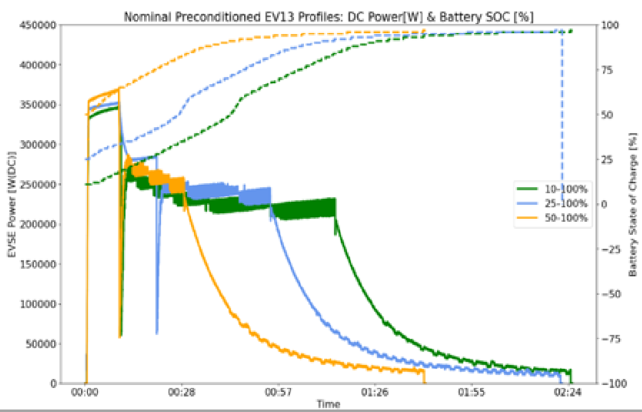
EV13_21_HD_>500V

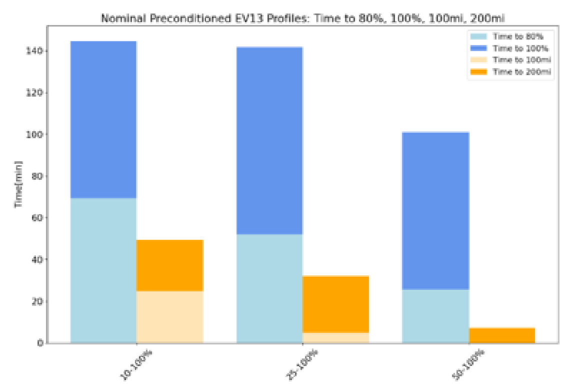
Page (2/2)

Temperature & Conditioning Variance

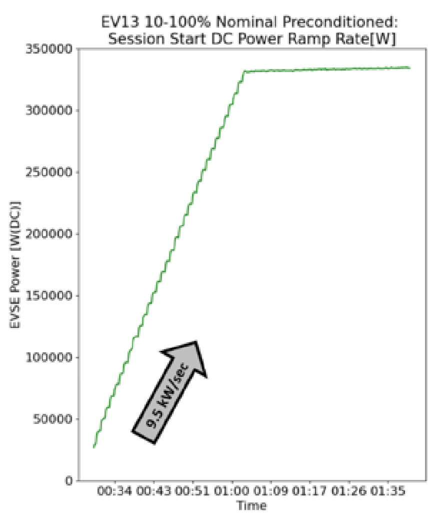


Start SOC Variance





Ramp Rate & SCM



EVSE Limited

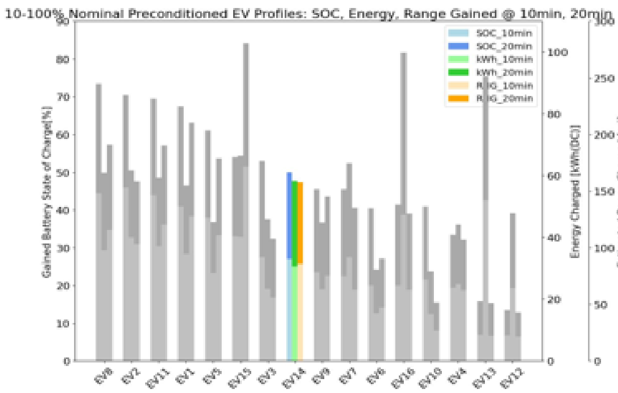
Adapters/Converters

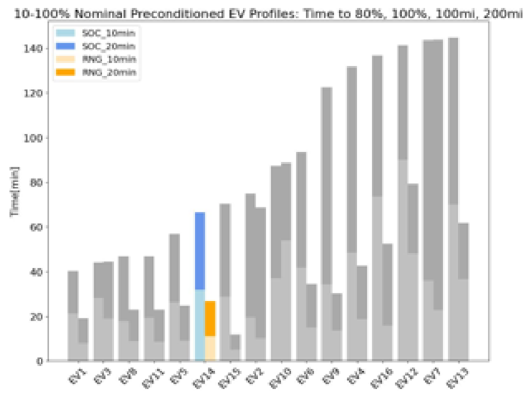
EV14_23_LD_<500V

Page (1/2)

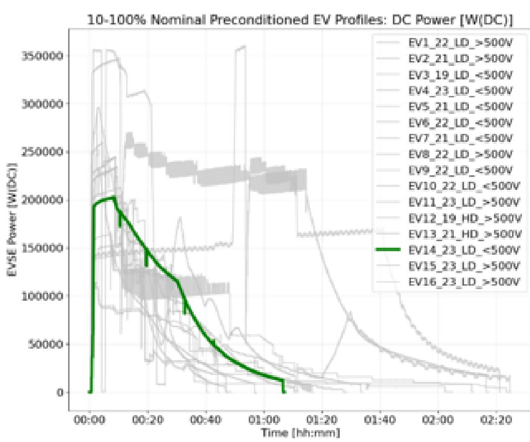
Vehicle Description	
Identifier	EV14
Model Year	2023
Vehicle Type	Light Duty
Nominal Charging Voltage	< 500VDC
Rated Usable Energy	100-150 kWh
Rated Max Charge Power	200-250 kW
Rated Charge Time (10-80%)	~ 20min
Rated Range	300-350 miles
EVSE Tested On	EVSE1_H1

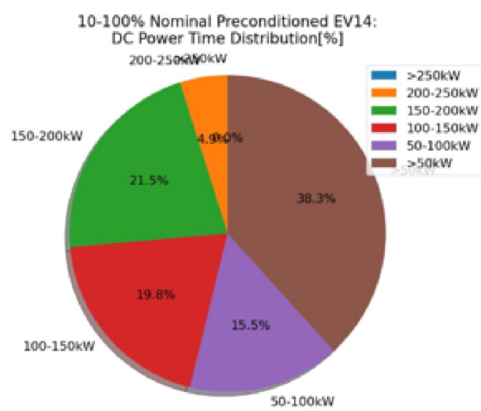
SOC, kWh, Range





DC Power



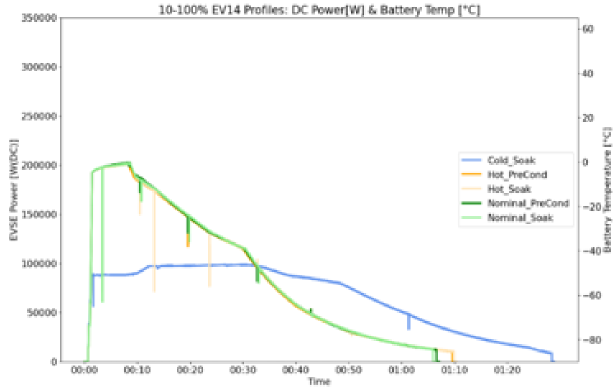


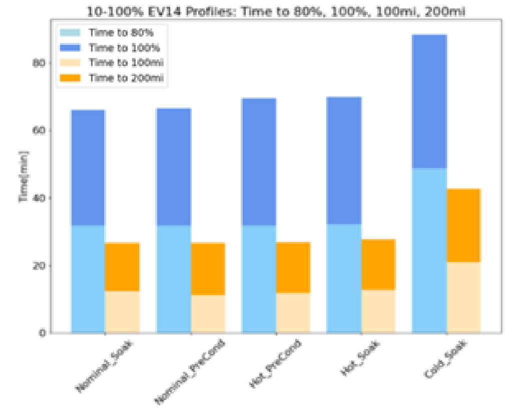
Testing Conditions	SOC: 10-80%				SOC: 10-100%						
	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	I_{peak} [A]	P_{peak} [kW]	Battery $Temp_{peak}$
Nominal PreCond	0:32	371	158	83	1:06	224	96	106	~500	~200	X
Nominal Soak	0:32	370	157	83	1:06	226	97	106	~500	~200	X
Hot PreCond	0:32	368	156	82	1:10	214	92	105	~500	~200	X
Hot Soak	0:32	370	157	83	1:10	215	92	106	~500	~200	X
Cold PreCond	X	X	X	X	X	X	X	X	X	X	X
Cold Soak	0:49	218	93	74	1:28	157	67	98	~250	~100	X

EV14_23_LD_<500V

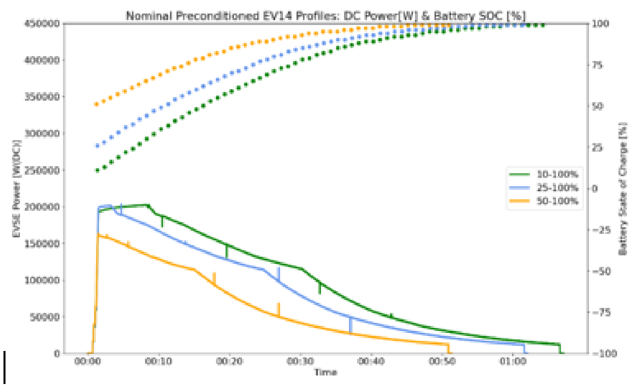
Page (2/2)

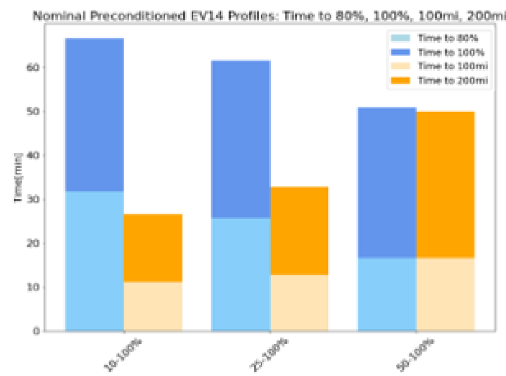
Temperature & Conditioning Variance



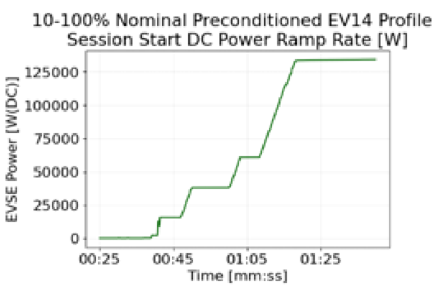


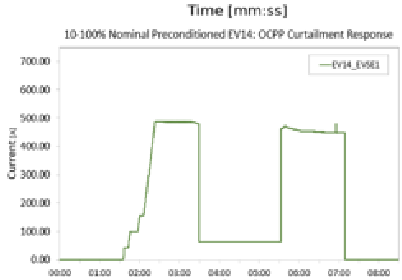
Start SOC Variance



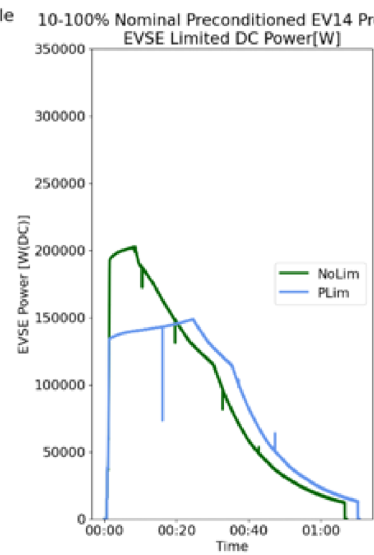


Ramp Rate & SCM





EVSE Limited



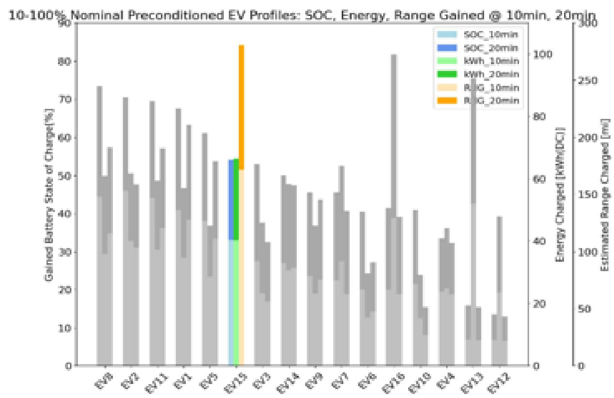
Adapters/Converters

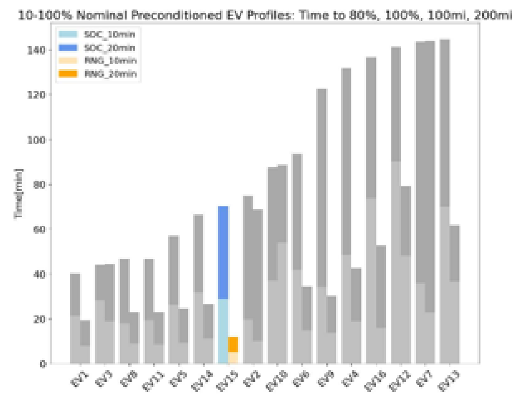
EV15_23_LD_>500V

Page (1/2)

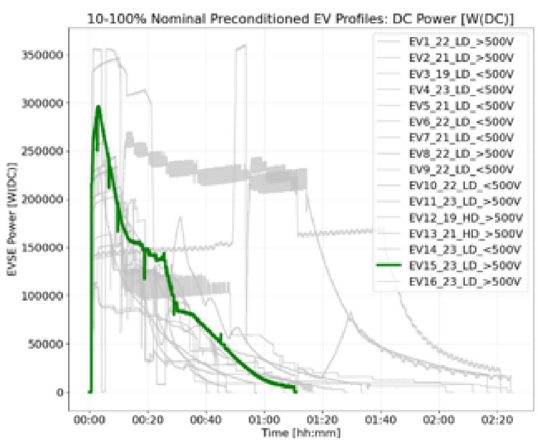
Vehicle Description	
Identifier	EV15
Model Year	2023
Vehicle Type	Light Duty
Nominal Charging Voltage	> 500VDC
Rated Usable Energy	100-150 kWh
Rated Max Charge Power	300-350 kW
Rated Charge Time (10-80%)	~ 20min
Rated Range	500-550 miles
EVSE Tested On	EVSE1_H1

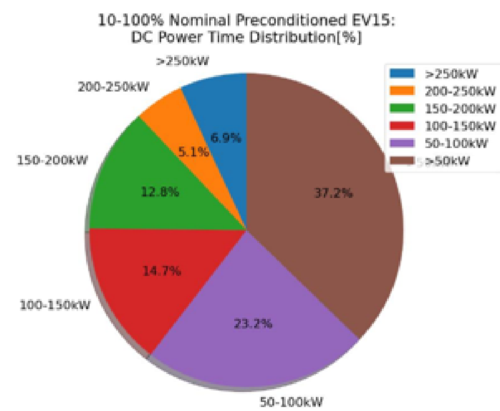
SOC, kWh, Range





DC Power



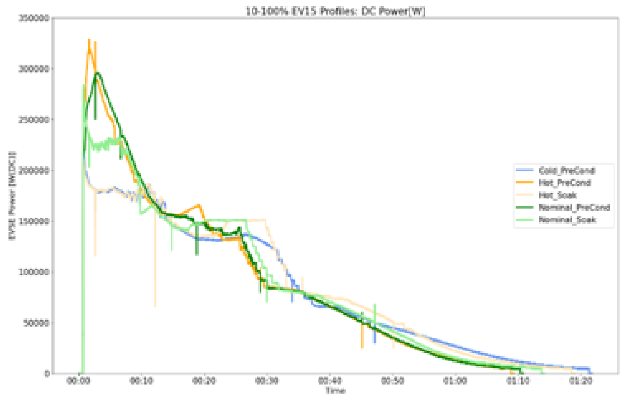


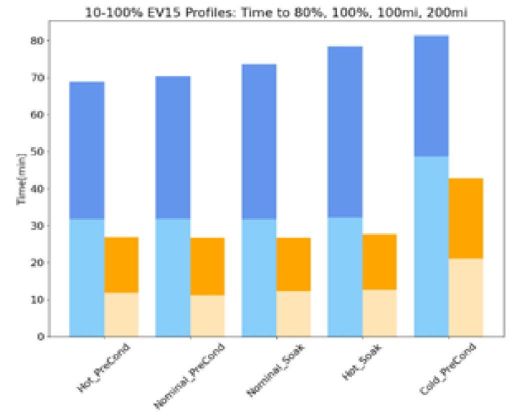
Testing Conditions	SOC: 10-80%				SOC: 10-100%						
	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	I_{peak} [A]	P_{peak} [kW]	Battery $Temp_{peak}$
Nominal PreCond	0:32	201	176	87	1:10	110	98	113	~350	~300	X
Nominal Soak	0:32	187	164	86	1:13	104	92	112	~350	~300	X
Hot PreCond	0:32	202	177	85	1:09	111	99	112	~400	~350	X
Hot Soak	0:32	173	150	87	1:19	99	87	113	~250	~200	X
Cold PreCond	0:49	167	145	86	1:21	93	82	110	~250	~200	X
Cold Soak	X	X	X	X	X	X	X	X	X	X	X

EV15_23_LD_>500V

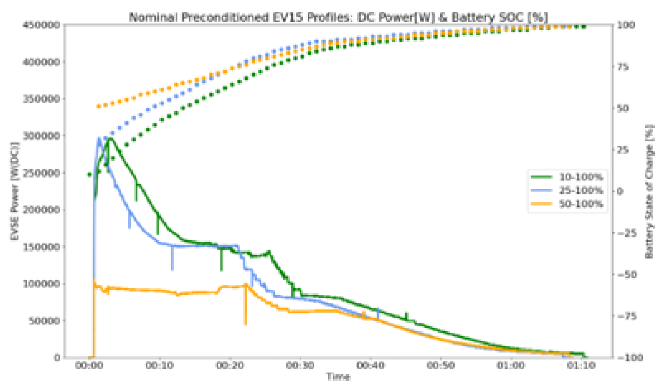
Page (2/2)

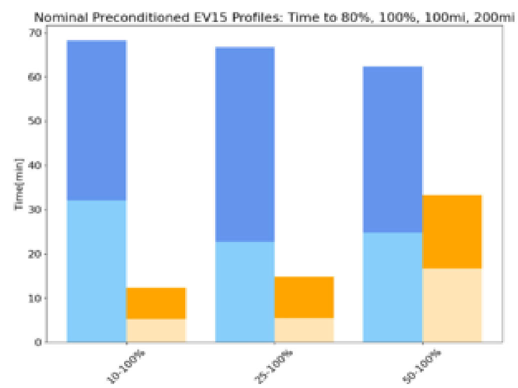
Temperature & Conditioning Variance



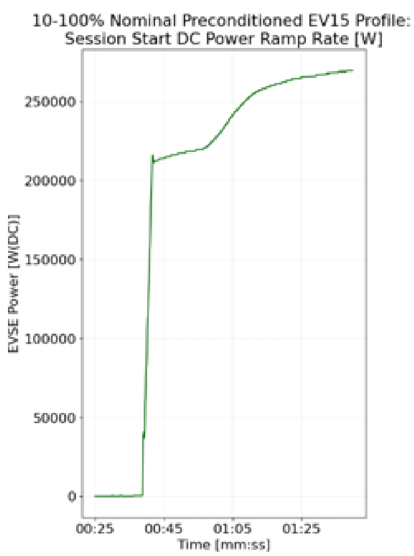


Start SOC Variance



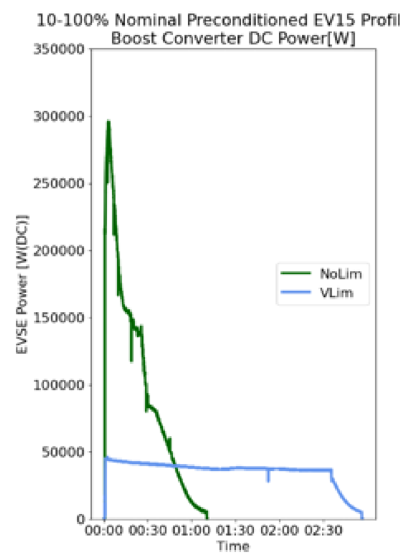


Ramp Rate & SCM



EVSE Limited

Adapters/Converters

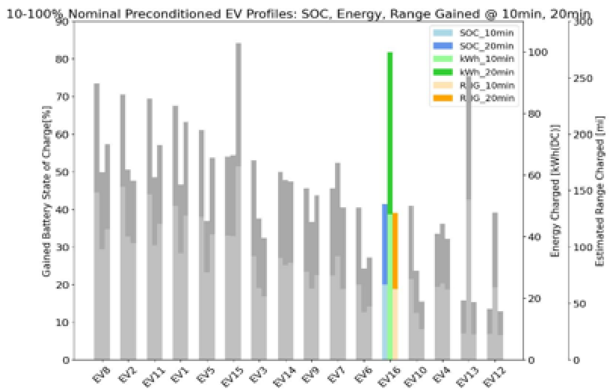


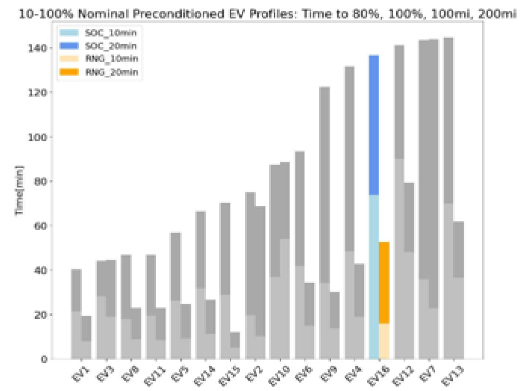
EV16_22_LD_>500V

Page (1/2)

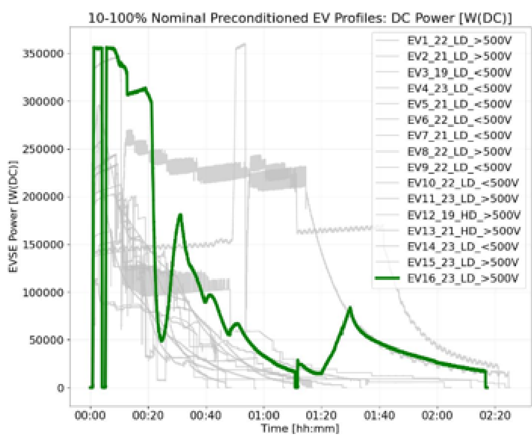
Vehicle Description	
Identifier	EV16
Model Year	2022
Vehicle Type	Light Duty
Nominal Charging Voltage	> 500VDC
Rated Usable Energy	200-250 kWh
Rated Max Charge Power	300-350 kW
Rated Charge Time (10-80%)	~ 20min
Rated Range	300-350 miles
EVSE Tested On	EVSE2_H1

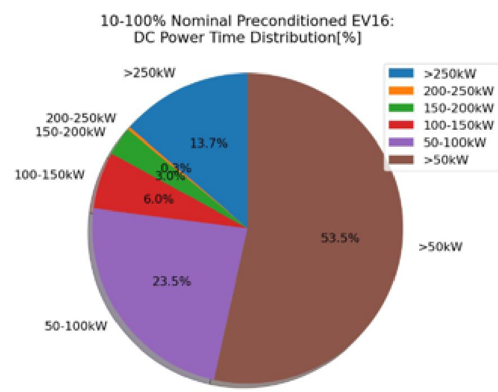
SOC, kWh, Range





DC Power



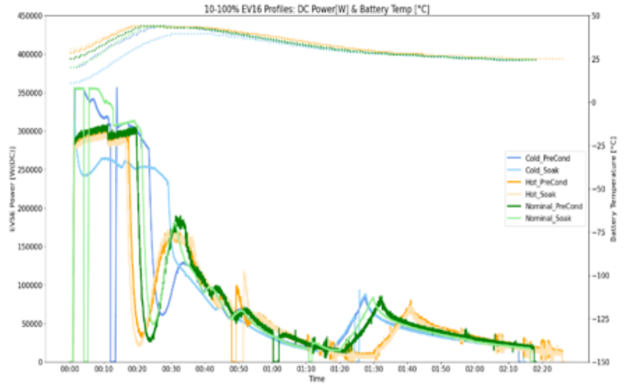


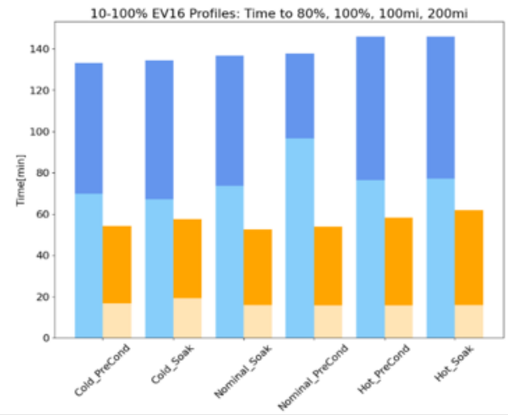
Testing Conditions	SOC: 10-80%				SOC: 10-100%						
	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	Time [h:m]	I_{avg} [A]	P_{avg} [kW]	E_{total} [kWh]	I_{peak} [A]	P_{peak} [kW]	Battery $Temp_{peak}$
Nominal PreCond	1:36	145	110	176	2:17	115	87	198	~400	~300	44°C
Nominal Soak	1:14	182	138	167	2:17	119	90	204	~500	~350	44°C
Hot PreCond	1:16	162	122	154	2:25	102	77	186	~400	~300	44°C
Hot Soak	1:17	158	118	150	2:25	99	74	180	~400	~300	44°C
Cold PreCond	1:10	189	143	164	2:13	120	91	201	~500	~350	44°C
Cold Soak	1:07	193	146	161	2:14	117	89	198	~450	~300	40°C

EV16_22_LD_>500V

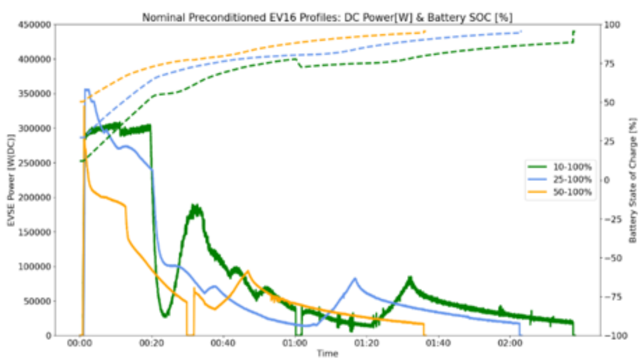
Page (2/2)

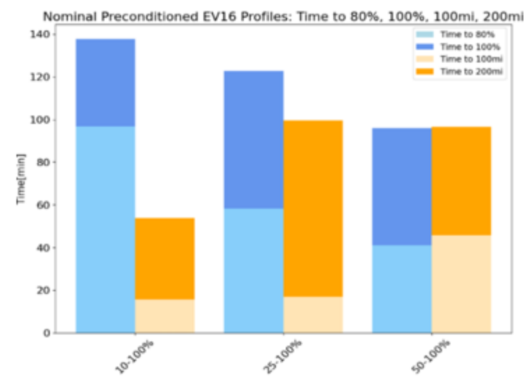
Temperature & Conditioning Variance



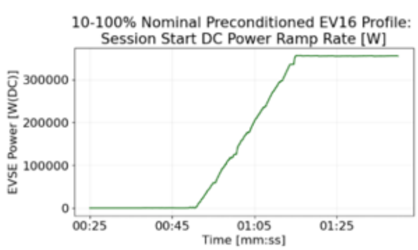


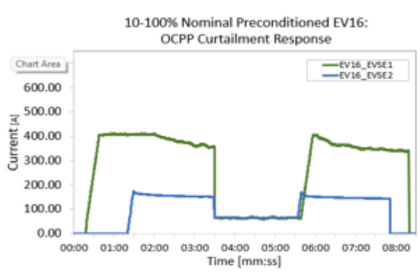
Start SOC Variance



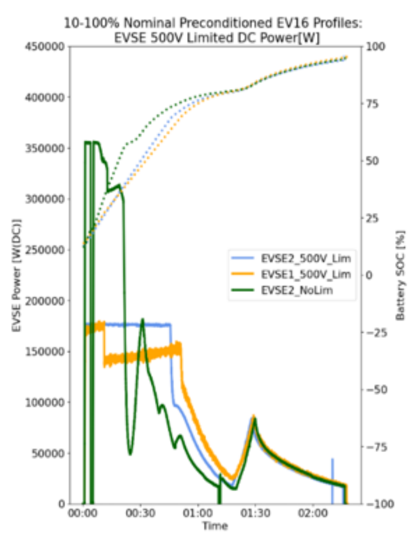


Ramp Rate & SCM





EVSE Limited



Adapters/Converters