Performance Evaluation of Direct Current Electric Vehicle Supply Equipment

Final Report

ET24SWE0025

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Executive Summary

This evaluation examined the comparative performance of alternating current (AC) and direct current (DC) electric vehicle supply equipment (EVSE) to assess charging efficiency, identify opportunities for energy savings, and estimate potential statewide impacts associated with broader DC EVSE deployment in California. The project team conducted testing under controlled laboratory conditions using a precision testbed built upon industry-accepted standards for efficiency and power quality measurement, ensuring results are representative of real-world operating behavior.

Across Phase 1 tested operating points, DC charging generally demonstrated higher conversion efficiency than AC systems. While AC EVSE operated in the 91 percent to 93 percent range, DC units achieved efficiencies between 95 percent and 97 percent, particularly at their default power-level operation. These results confirm that DC charging offers measurable energy performance advantages that can translate to reduced energy losses and lower operational costs under certain load conditions. In addition to efficiency benefits, DC EVSE can substantially reduce charging duration by delivering power directly to the vehicle battery at significantly higher rates than typical AC EVSE. Reduced charging times can improve vehicle availability and enhance user convenience.

Several of the tested units were ENERGY STAR®–certified—two AC and one DC. Certification status, however, did not consistently correspond with higher measured efficiency. The certified DC unit outperformed all others, while the certified AC chargers performed comparably to or below some non-certified models. This suggests that while certification establishes a useful baseline for product quality, real-world efficiency is still strongly influenced by equipment design and system integration. These findings underscore the importance of advancing performance-based efficiency benchmarks that better capture the combined behavior of charging equipment and vehicle systems.

Economic analysis found that DC EVSE can yield modest energy cost savings, averaging $10 to $27 per vehicle per year under prevailing time-of-use rate structures. However, higher upfront costs—around $10,000 per unit compared to roughly $400 for typical Level 2 AC chargers—remain a key barrier to adoption. Continued cost reductions driven by technology maturation, manufacturing scale, and targeted incentives will be critical to achieving broader market penetration.

At the recommendation of Southern California Edison, the team conducted a second phase of testing to evaluate charging performance during continuous vehicle charging sessions. A subset of two AC and two DC EVSE systems, previously evaluated in Phase 1 were tested over a representative charging event spanning approximately 10 percent to 80 percent battery state of charge. This supplemental evaluation provided additional insight into charging efficiency and power delivery throughout an extended charging session and complemented the discrete state-of-charge testing performed during Phase 1.

Applying these observed efficiency differences to California's current light-duty zero-emission vehicle fleet of roughly 1.9 million vehicles indicates potential statewide energy savings of about 173 gigawatt-hours annually, equivalent to approximately 0.06 percent of California's total 2023 electricity consumption and avoiding 50,269,075 kilograms of carbon dioxide equivalent emissions annually. Although the per-vehicle savings are modest, the aggregate impact is meaningful in the context of California's clean transportation and emissions reduction goals.

Abbreviations and Acronyms

Acronym	Meaning
AC	Alternating current
CAN	Controller Area Network
CCS	Combined charging system
CLTC	California Lighting Technology Center
DC	Direct current
EV	Electric vehicle
EVSE	Electric vehicle supply equipment
gCO_2e/MJ	Grams of carbon dioxide equivalent per megajoule
GWh	Gigawatt-hour
I	Current
IEC	International Electrotechnical Commission
kW	Kilowatt
kWh	Kilowatt-hour
OBC	Onboard charger
PEV	Plug-in electric vehicle
PG&E	Pacific Gas and Electric
SAE	Society of Automotive Engineers
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
TOU	Time-of-use

Acronym	Meaning
V	Volts
ZEV	Zero-emission vehicle

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Introduction

California's commitment to achieving carbon neutrality by 2045 is deeply intertwined with its efforts to decarbonize the transportation sector. The state's ambitious goals, such as phasing out sales of new internal combustion engine vehicles by 2035 and transitioning to a fully zero-emission vehicle (ZEV) fleet, underline the necessity of widespread electric vehicle (EV) adoption. To support this transformation, robust and reliable electric vehicle supply equipment infrastructure is critical. As EV ownership grows, so does the demand for charging solutions that are efficient, accessible, and capable of meeting diverse user needs across California.

Currently, two primary types of electric vehicle supply equipment (EVSE) architecture are commercially available: alternating current (AC) EVSE and direct current (DC) EVSE. Both play essential roles in the EV ecosystem, catering to different use cases and charging environments.

AC EVSE is predominantly used in residential, workplace, and public settings due to its cost-effectiveness and compatibility with existing electrical systems. AC EVSE provides alternating current power to the EV, where it is converted to direct current by the onboard charger (OBC) within the vehicle before being stored in the vehicle's battery.

In contrast, DC EVSE is found more often in high-speed charging applications, typically in public and commercial settings. DC EVSE delivers direct current power to the EV from the charger itself, only needing to undergo a potential DC-to-DC conversion before being stored in the vehicle's battery. The ability to deliver higher charging power allows DC EVSE to significantly reduce charging durations compared to conventional AC EVSE, making it particularly well suited for public charging services and fleet operations where minimizing charging time is a priority.

The key distinction between AC and DC EVSE lies in the power transmission pathway. With AC EVSE, the power undergoes an AC-to-DC conversion within the vehicle. Early research suggests that internal AC-to-DC conversion in the OBCs, while compact and cost-effective, are generally less efficient than the larger, more advanced converters used in DC EVSE systems. This means DC EVSE, in theory, may result in a more efficient power transmission process by increasing conversion efficiency and potentially reducing conversion steps when paired with a DC-supplied electrical grid where power is generated and distributed at the site.

Understanding the strengths and limitations of these two architecture types is essential for optimizing California's charging network and ensuring it aligns with the state's clean energy and climate goals. This project explores the performance of both AC and DC EVSE to provide data-driven insights that will guide future infrastructure investments and policy decisions.

Background

EVSE is standardized under the Society of Automotive Engineers (SAE) J1772 specification, which defines the technical parameters for AC and DC charging systems. Each charging system is further divided into levels based on voltage, current, and operational capacity.

AC Charging Levels

AC charging systems utilize single-phase alternating current and are divided into two levels based on nominal supply voltage and max current (Table 1).

> **AC Level 1**: Operates at 120 volts (V) with single phase input.
>
> **AC Level 2**: Operates at 240 V with single phase input.

Table 1: AC charging electrical ratings.

Charge Method	Nominal Supply Voltage (V)	Max Current (Amps-continuous)
AC Level 1	120 VAC, 1-phase	≤ 50 A
AC Level 2	208 to 240 VAC, 1-phase	≤ 80 A

Source: SAE J1772 (SAE, 2017).

DC Charging Levels

DC charging systems deliver direct current power to the vehicle and are categorized into the two levels defined in Table 2.

Table 2: DC charging electrical ratings.

Charge Method	EVSE DC Output Voltage (VDC)	Max Current (Amps-continuous)
DC Level 1	50-1000*	80
DC Level 2	50-1000*	500**

Source: SAE J1772.

The parameters defined in SAE J1772 ensure compatibility and standardization across EVSE systems, forming the basis for the classification and operation of charging infrastructure.

Objectives

The primary objective of this project was to evaluate the energy efficiency of commercially available EVSE, specifically comparing AC and DC charging systems under controlled conditions. This evaluation aimed to quantify energy losses across the charging pathway and assess potential energy savings from broader adoption of efficient DC EVSE.

The project also sought to characterize a representative OBC and plug-in electric vehicle (PEV) components to support accurate modeling of real-world charging scenarios. A standardized laboratory methodology was developed to enable repeatable and consistent testing of both AC and DC systems across various operating conditions.

Lastly, the project aimed to model statewide impacts of EVSE efficiency, including energy savings, demand reduction, and greenhouse gas emissions. Findings from this evaluation are intended to support utility program development, inform incentive strategies, and identify future opportunities for efficient EVSE deployment across California's growing electric vehicle market.

Product Selection

Approach

The selection of products for this evaluation was carefully designed to ensure a robust and comprehensive comparison of AC and DC EVSE. Our selection criteria focused on market prevalence, certification status, application (residential or commercial), and alignment with the project's testing objectives. This strategy ensured that the selected products reflect the diversity and practicality of EVSE systems in real-world applications. Additionally, the team chose onboard chargers to establish a baseline for understanding their role and performance within the charging ecosystem. While the products are listed in no particular order, final selection for testing depended on the acquisition process and availability.

AC EVSE

The focus for AC EVSE was on identifying systems that are both popular and prolific in the current market. To capture a comprehensive range of use cases, the product list included both residential and commercial models as well as devices with and without ENERGY STAR® certification to allow for a comparative analysis of their efficiency and variability. By including products from both categories, the evaluation aimed to provide a nuanced understanding of how certification status impacts performance.

Table 3: AC EVSE selected product list.

ID	Level	Plug Type	Power	Market	Energy Star	Price
AC-C01	AC Level 2	J1772	12.0 kW	Residential	Certified	$599
AC-C02	AC Level 2	NACS	11.5 kW	Residential	Certified	$420

ID	Level	Plug Type	Power	Market	Energy Star	Price
AC-C03	AC Level 2	J1772	11.5 kW	Residential	Certified	$429
AC-C04	AC Level 1 & 2	J1772	3.8 kW	Residential	Not certified	$130
AC-C05	AC Level 2	J1772	11.5 kW	Residential	Not certified	$419
AC-C06	AC Level 2	J1772	19.2 kW	Commercial	Certified	$4,699
AC-C07	AC Level 2	J1772	11.2 kW	Commercial	Certified	$3,320
AC-C08	AC Level 2	J1772	7.2 kW	Commercial	Not certified	$5,250
AC-C09	AC Level 2	J1772	7.7 kW	Commercial	Certified	$428
AC-C10	AC Level 2	J1772	7.7 kW	Commercial	Not certified	$1,449

Source: CLTC, Manufacturer Specifications.

DC EVSE

The selection criteria for DC EVSE were designed to ensure comparability with AC EVSE in terms of power throughput. The team gave priority to DC EVSE systems with power under 40 kilowatts (kW), aligning them with the performance range of AC EVSE while preserving the distinct operational characteristics of DC systems. This approach allowed for a balanced evaluation of their efficiency and power delivery capabilities.

The team considered both residential-focused and commercial-grade DC chargers to reflect the diverse applications of DC charging. However, the availability of residential DC solutions was limited, which narrowed the scope of residential-focused products in the evaluation.

The selected DC EVSE systems emphasize compatibility with combined charging system (CCS) chargers, as CCS represents the dominant standard for DC charging. Its widespread adoption and interoperability make it a critical benchmark for assessing DC EVSE performance.

Table 4: DC EVSE selected product list.

ID	Level	Plug Type	Power	Market	ENERGY STAR	Price
DC-C01	DC Level 1	CCS1	24 kW	Commercial	Certified	$10,935
DC-C02	DC Level 1	CCS1	25 kW	Commercial	Not certified	$10,052
DC-C03	DC Level 1	CCS1	30 kW	Commercial	Not certified	$12,830
DC-C04	DC Level 1	CCS1	30 kW	Commercial	Certified	$11,900
DC-C05	DC Level 1	CCS1	21 kW	Commercial/ residential	Not certified	$9,750
DC-C06	DC Level 1	CCS1	10 kW	Commercial/ residential	Not certified	$4,500

Source: CLTC, Manufacturer Specifications.

Onboard Chargers

Onboard chargers were selected based on their prevalence in the market and the degree to which their designs are well understood. The OBCs used in this study are representative of current EV technology, ensuring that the testing results align with real-world conditions and provide a reliable baseline for comparison with DC EVSE.

Table 5: Onboard charger list for AC testbed.

Manufacturer	Found In
OBC-C01	4 vehicle models
OBC-C02	2 vehicle models
OBC-C03	2 vehicle models
OBC-C04	1 vehicle model

Source: CLTC.

Acquired Systems

The project team acquired four AC Level 2 systems, four DC Level 1 systems, and two onboard chargers for this evaluation. The AC chargers' power ranged from 3.8 kW to 12 kW, with a combination of ENERGY STAR–certified products, while the DC chargers ranged from 10 kW to 25 kW, with only one ENERGY STAR–certified product. The research team included two OBCs to support both charging pathways. For AC testing, the onboard charger integrated into a vehicle with low mileage (15,000) was used to ensure dependable data collection under real-world charging conditions. For DC testing, a separate OBC was set up on the testbed to enable controlled measurements of DC charging behavior.

The acquired systems are summarized in Table 6 and correspond to models drawn from the proposed lists presented in Table 3 through Table 5. Final selection was determined by system availability, quality of supporting documentation, and practical considerations during procurement.

Our acquisitions emphasized residential-focused systems, as these are central to enabling overnight charging at lower electrical rates. While residential AC units are widely available and therefore form the bulk of the acquisition set, residential-scale DC systems with comparable power levels remain limited in the current market. For this reason, several of the DC chargers obtained for testing were commercial offerings. Electrically, these units are functionally identical to their residential counterparts, with differences primarily in packaging, cyber security certifications, and market positioning. Their inclusion allows for representative efficiency testing while highlighting the expectation that residential DC systems of similar design will become more widely available over time.

Table 6: Acquired systems.

AC EVSE	DC EVSE	OBC
AC EVSE 1: AC-C01	DC EVSE 1: DC-C06	Testbed OBC: OBC-C01
AC EVSE 2: AC-C05	DC EVSE 2: DC-C05	Vehicle OBC: OBC-C02
AC EVSE 3: AC-C09	DC EVSE 3: DC-C01	
AC EVSE 4: AC-C04	DC EVSE 4: DC-C02	

Source: CLTC.

Testing Methodology

Testing Objectives

The team designed the testing phase of this project to provide a comprehensive evaluation of both AC and DC EVSE under controlled laboratory conditions. Our objectives were to assess performance, efficiency, and operational behavior across various scenarios, ensuring meaningful insights into the strengths and limitations of different EVSE systems. Key testing objectives included:

1. **Assessing charger behavior across varying battery levels**: The study will evaluate how chargers perform under different starting states of battery charge, ranging from low to high states of charge, e.g., 10 percent to 90 percent. This will help determine how charging efficiency, power delivery, and operational behavior change with the battery's charge level.
2. **Evaluating charging pathway efficiency across varying EVSE and electrical architectures:** The testing will focus on characterizing energy flow and losses along the entire charging pathway, from the power source to the EV battery. By analyzing both AC and DC EVSE systems, the study will identify inefficiencies and provide comparisons of performance between different electrical architectures.

The research team aligned the development of the testing methodology with established industry standards to ensure consistency and technical rigor. The ENERGY STAR Test Method for Electric Vehicle Supply Equipment (Energy Star, 2023) and SAE J2894 – Power Quality Requirements for Plug-In Electric Vehicle Chargers (SAE , 2025) were referenced to guide the placement of metering points, define measurement accuracy requirements, and establish appropriate data polling intervals.

Incorporating these standards helped ensure that the test setup and data collection approach were consistent with recognized best practices for EVSE performance evaluation.

Testbed Design

To evaluate the performance of both AC and DC EVSE systems, a modular testbed was necessary. This testbed is designed to accommodate slight variations in electrical architecture between the two charging systems, ensuring flexibility and accuracy during testing.

The testbed focused on capturing power data at three critical points in the charging process: power as it is supplied to the EVSE from the power source, power as it exits the EVSE through the charge cable, and power as it is delivered to the EV's battery. These points provide a comprehensive view of energy flow and efficiency throughout the charging process. Testbeds and laboratory environmental conditions adhered to International Electrotechnical Commission (IEC) 62301 unless otherwise noted.

A high-level overview of the testbed in both an AC and DC EVSE configuration is provided in Figure 1 and Figure 2, illustrating the measurement points and necessary components.

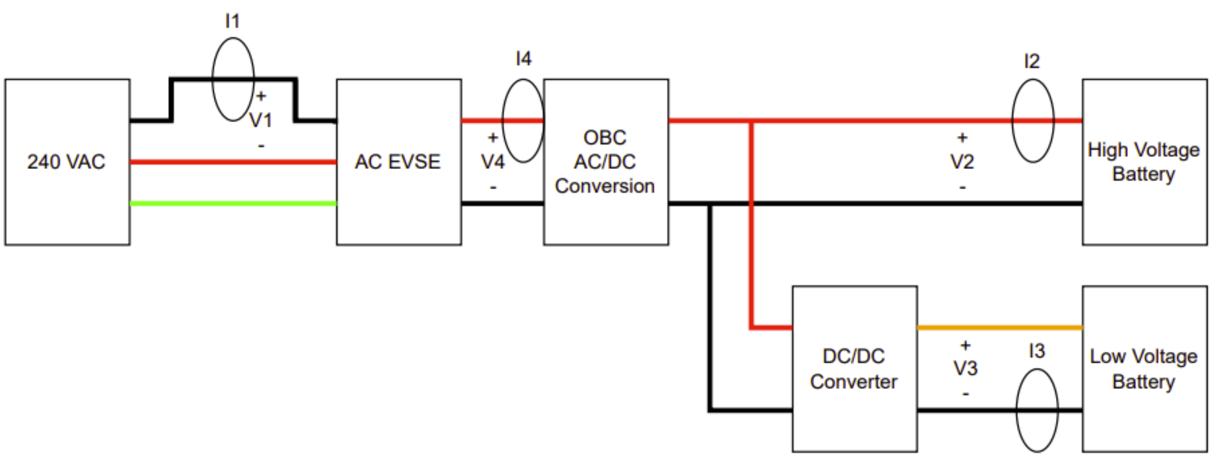

Figure 1: AC configuration for testbed.

Source: CLTC.

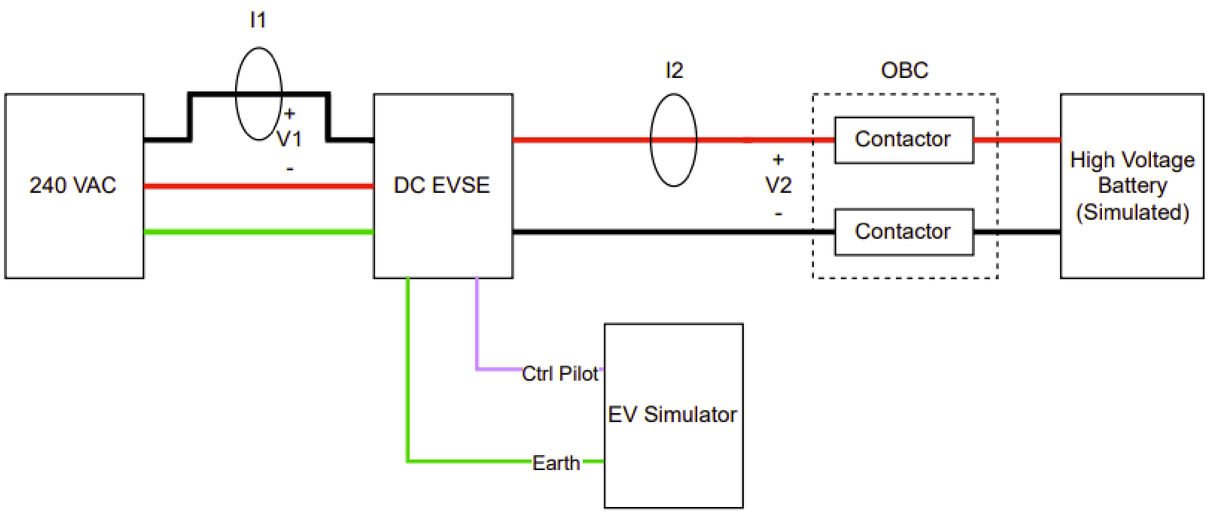

Figure 2: DC configuration for testbed.

Source: CLTC.

In both testbed configurations, power to the EVSE was supplied by a regulated power source. Metering points for each design are clearly marked along the transmission pathways, as indicated by the voltage (V) and current (I) indication in the schematics. The AC testbed included additional metering to include monitoring of auxiliary loads, such as the connected low-voltage battery, and conversion losses. DC measurements were simplified due to the direct connection aspect of the testbed, where energy after leaving the DC EVSE directly flowed into the battery. Precision measurements were conducted using Xitron XT2640 power analyzers at a data poll rate of one second. AC metering points were paired with Continental Control System current transformers, while DC metering points utilized a DC shunt or Fluke i30 current clamp to provide accurate measurements of direct current, all adhering to revenue grade accuracy requirements. Accuracy specifications for the Xitron power analyzers can be viewed in Table 7 and further specifications can be found in Appendix A, available upon request.

Table 7: Accuracy specification for Xitron XT2640.

Specification	Accuracy
Voltage	0.1%
Current	0.1%
Power	0.05%

Source: Xitron.

The metering approach for both AC and DC EVSE was designed to be as consistent as possible to ensure comparability across the two architectures. Consistency was maintained at the EVSE input, while differences were required downstream of the EVSE to account for the distinct electrical characteristics of AC and DC pathways. In those cases, functionally equivalent metering devices were selected so that accuracy and reliability were preserved across both setups.

Test Scenarios

Two groups of tests were evaluated to provide a structured approach for assessing EVSE performance. The first group targeted real-world charging conditions by varying the battery state of charge (SOC), while the second group focused on controlled power throughput variations with SOC held constant. This framework ensured that both practical operating behavior and underlying efficiency characteristics were captured.

Phase 1. SOC Efficiency Testing

The first group of scenarios evaluated charger behavior across a range of battery SOC. Tests were conducted with the battery at 10 percent, 25 percent, 75 percent, and 90 percent SOC, with the charger operating at its default power delivery strategy in each case. Each test was conducted over a fixed 10-minute duration to limit SOC variance and provide a consistent operational window for both AC and DC EVSE units while limiting factors such as temperature rise, adaptive charging algorithms, and tapering behavior. The 90 percent SOC testing was only available on the DC systems as the AC vehicle testbed limited charging above 80 percent to maintain battery state of health. These scenarios were designed to capture how efficiency, power delivery, and operational behavior evolve as the battery progresses through the charging cycle. The focus was on understanding how conversion losses shift as charging current tapers at higher SOC levels, and whether different products exhibited consistent or divergent patterns of performance. The scenarios for this group are summarized in Table 8.

Table 8: SOC testing scenarios.

Scenario	Battery State	Target Power Throughput
1	10	Default
2	25	Default
3	75	Default
4	90*	Default

*The OBC vehicle testbed limited charging only when SOC was lower than 80 percent.

Source: CLTC.

Phase 1. Power Throughput Testing

The second group of scenarios concentrated on the influence of charging power level while holding battery SOC constant at 10 percent. By fixing the SOC, the research team could attribute variations in performance directly to changes in throughput rather than to battery condition. Tests were run at multiple target power levels, 2 kW, 5 kW, and 10 kW, to map the relationship between power level, conversion efficiency, and losses across both AC and DC architectures. Power levels of EVSE are not standardized, and since the acquired systems range from 3.8 kW to 25 kW, the power targets were intended to give at least one comparable power level for each test. Additionally, a 20 kW level was assessed, but the DC testbed could not support power delivery at this level even though the DC EVSEs could support it, which is a common limitation to many current EVs. This group of scenarios provided a complementary perspective, highlighting how the design of EVSE impacts energy efficiency at different load levels. The scenarios for this group are summarized in Table 9.

Table 9: Power throughput test scenarios.

Scenario	Battery State	Target Power Throughput
5	10	2 kW
6	10	5 kW*
7	10	10 kW*

*Power targets were only assessed if the throughput level was achievable on EVSE.

Source: CLTC.

TEST PROCEDURE

The team followed a standard procedure for each test to maintain consistency across all AC and DC scenarios. The sequence of steps was designed to ensure comparable measurements while accommodating both SOC and power throughput variations.

The procedure for each test was as follows:

1. Prepare the testbed for either AC or DC operation.
2. Install the selected EVSE in the testbed configuration.
3. Verify that current transformers and other metering devices are correctly installed.
4. Energize the system.
5. Adjust EVSE settings or testbed conditions to match the test scenario (SOC target or power target).
6. Initiate data recording on the power analyzer.
7. Start charging session for 10 minutes.

8. End data recording and deenergize system or return to step 5 for new scenario.

Phase 2. Extended Time Series Vehicle Charging Testing

At the request of Southern California Edison (SCE), the team conducted additional phase 2 testing to evaluate charging performance under extended-duration vehicle charging conditions. Unlike the primary SOC efficiency tests, which evaluated charger operation at discrete battery states, the expanded testing measured charging behavior continuously—from 10 percent to 80 percent battery state of charge—using the electric vehicle testbed. Testing was performed for a subset of AC and DC EVSE systems, one of which is shown in Figure 3 below.

For AC testing, we used the existing vehicle-based test configuration. For DC testing, we modified the laboratory testbed from the original simulated battery configuration to a vehicle-based charging configuration to enable direct comparison of charging behavior across charging architectures. These tests were intended to capture efficiency trends, power delivery characteristics, and operational behavior over a representative charging session.

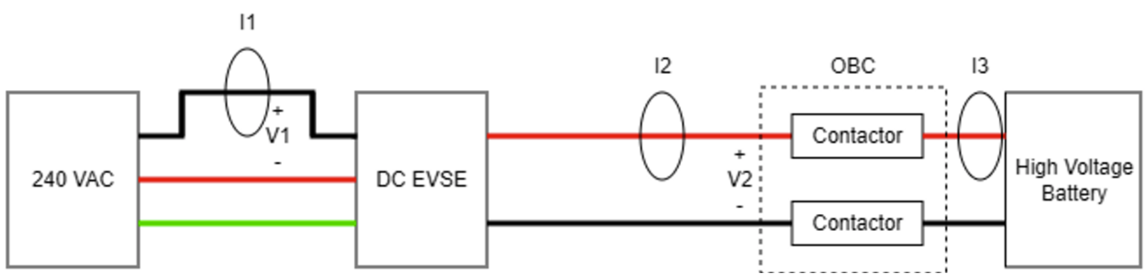

Figure 3: Modified DC testbed for phase 2 testing.

Source: CLTC.

Results: Phase 1

The results are organized by EVSE type, beginning with AC systems followed by DC systems. Power conservation efficiencies and power measurements are reported as averages of all data points measured throughout the 10-minute test period. Additionally, observed trends are presented in conjunction with the tables and figures prepared for each test.

It is important to note that AC EVSE testing was conducted using a vehicle-based testbed, while DC EVSE testing was performed on a simulated testbed. As a result, the AC results reflect measured changes in real SOC, whereas the DC results present simulated SOC values aligned with the test setup.

AC EVSE 1

As shown in Table 10, AC EVSE 1 recorded average efficiencies between 91.61 percent and 92.50 percent under default charging conditions. The corresponding average power remained stable at approximately 6.9 kW across all possible SOC test points.

Table 10: AC EVSE 1 SOC testing scenario results.

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
1	9.99%	13.04%	6930.02	91.61%
2	24.96%	27.95%	6916.69	92.12%
3	75.01%	77.69%	6952.99	92.50%
4	N/A*	N/A*	N/A*	N/A*

*Range exceeded testbed SOC capabilities.

Source: CLTC.

SOC testing results in Figure 4 showed efficiency starting at 91.6 percent at 10 percent SOC and rising gradually to 92.5 percent at 75 percent SOC. The trend was upward at 10 percent SOC and fairly flat at 25 percent and 75 percent SOC.

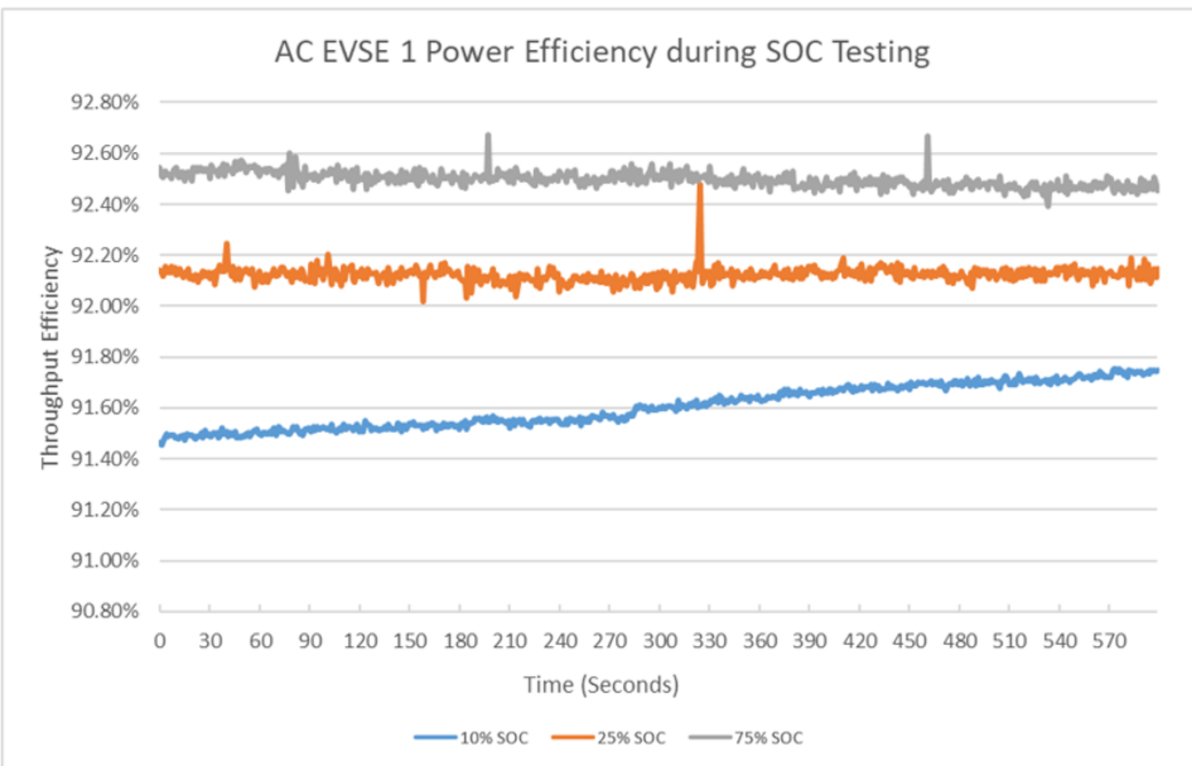

Figure 4: AC EVSE 1 power efficiency during SOC testing.

Source: CLTC.

For the power throughput scenarios, Table 11 shows efficiencies of 92.1 percent at approximately 2.2 kW and 93 percent at approximately 5.5 kW. These values indicate modest gains as throughput increased.

Table 11: AC EVSE 1 power throughput testing scenario results.

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
5	10.20%	11.32%	2166.47	92.10%
6	11.32%	13.66%	5486.94	93.03%
7	N/A*	N/A*	N/A*	N/A*

*Range exceeded EVSE power capabilities.

Source: CLTC.

The graph in Figure 5 showed a generally flat trend across the tested load range, with no noticeable increase or decrease in efficiency. However, variability was more pronounced at the lower power levels, with efficiency values at approximately 2 kW exhibiting the greatest scatter. At approximately 5 kW, results were somewhat steadier but still showed more variation than the default power target, which remained the most consistent.

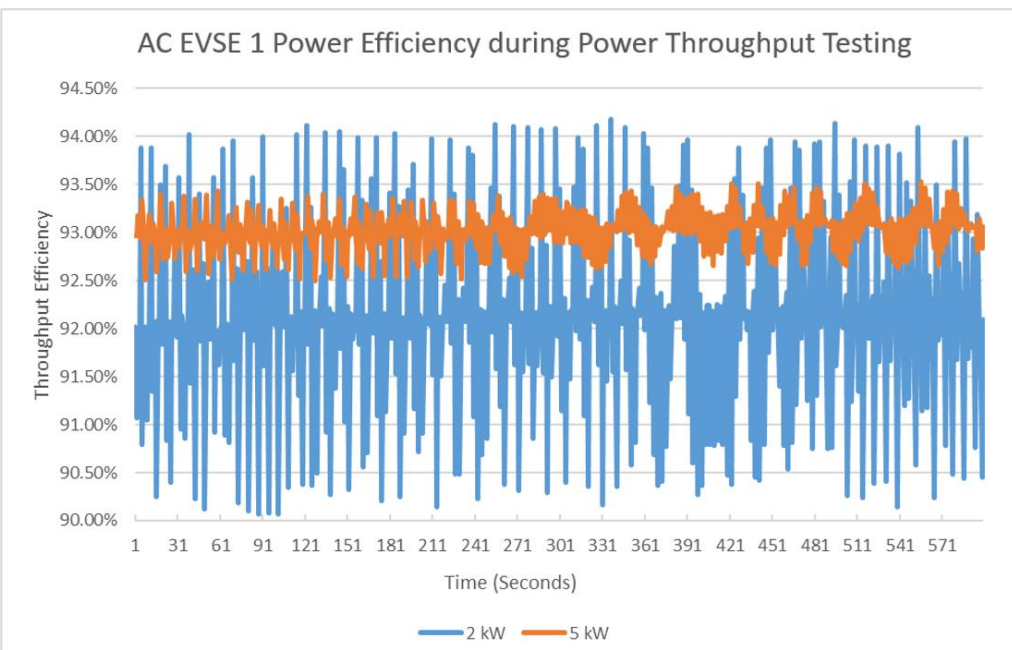

Figure 5: AC EVSE 1 power efficiency during power throughput testing.

Source: CLTC.

AC EVSE 2

According to Table 12, AC EVSE 2 achieved efficiencies ranging from 91.44 percent to 92.54 percent, with average power near 6.9 kW in default operation.

Table 12: AC EVSE 2 SOC testing scenario results.

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
1	9.97%	13.10%	6912.36	91.44%
2	25.04%	27.92%	6972.06	92.36%
3	74.61%	77.28%	6944.98	92.54%
4	N/A*	N/A*	N/A*	N/A*

*Range exceeded testbed SOC capabilities.

Source: CLTC.

SOC results in Figure 6 showed efficiency beginning at 91.4 percent at 10 percent SOC and increasing steadily to 92.5 percent at 75 percent SOC. The curve remained stable at higher SOC levels without any major declines.

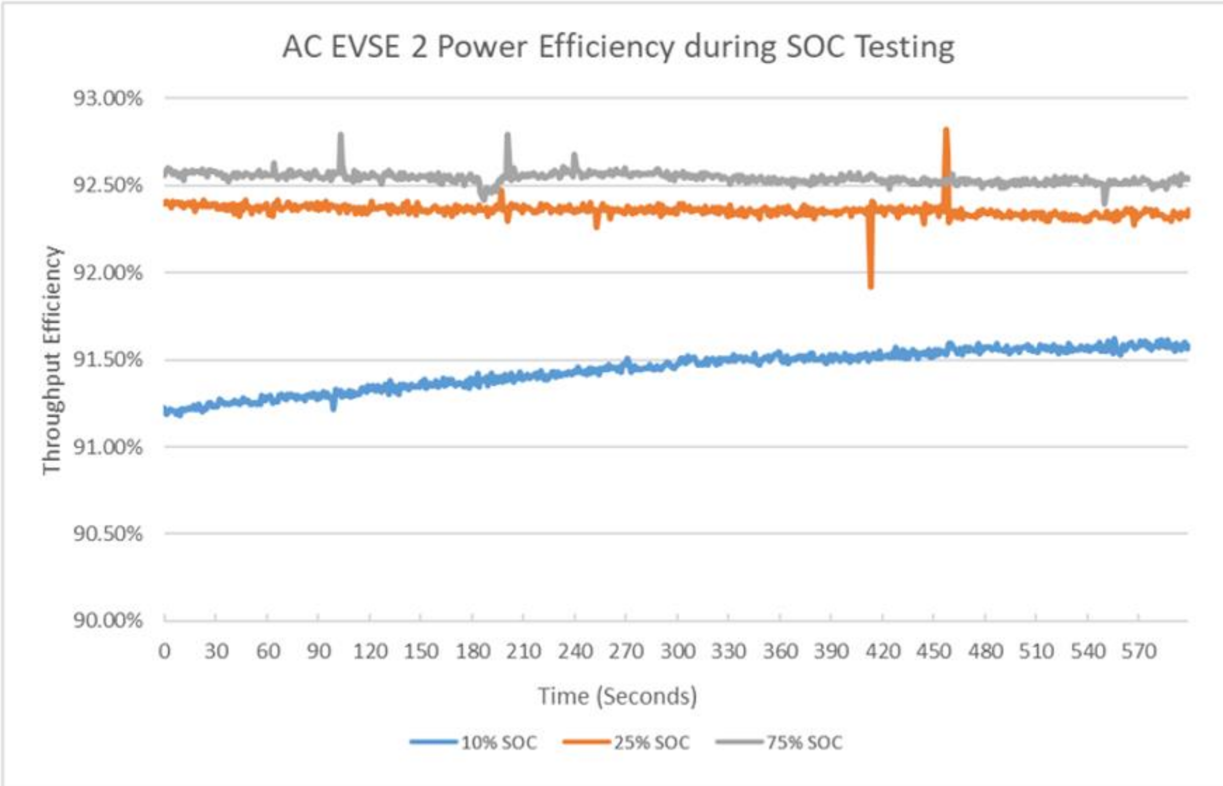

Figure 6: AC EVSE 2 power efficiency during SOC testing.

Source: CLTC.

In the power throughput tests, Table 13 shows efficiencies of 92.52 percent at approximately 2.2 kW and 93.24 percent at approximately 5.5 kW. These results highlight a modest improvement in efficiency with increasing load.

Table 13: AC EVSE 2 power throughput testing scenario results.

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
5	10.70%	11.72%	2171.24	92.52%
6	11.72%	13.60%	5502.91	93.24%
7	N/A*	N/A*	N/A*	N/A*

*Range exceeded EVSE power capabilities.

Source: CLTC.

As illustrated in Figure 7, the power curve for AC EVSE 2 remained relatively flat across the tested load range, with efficiency values showing little overall increase or decrease. Variability was most apparent at approximately 2 kW, while the results at approximately 5 kW were steadier but still less consistent than at the default power response, similar to AC EVSE 1.

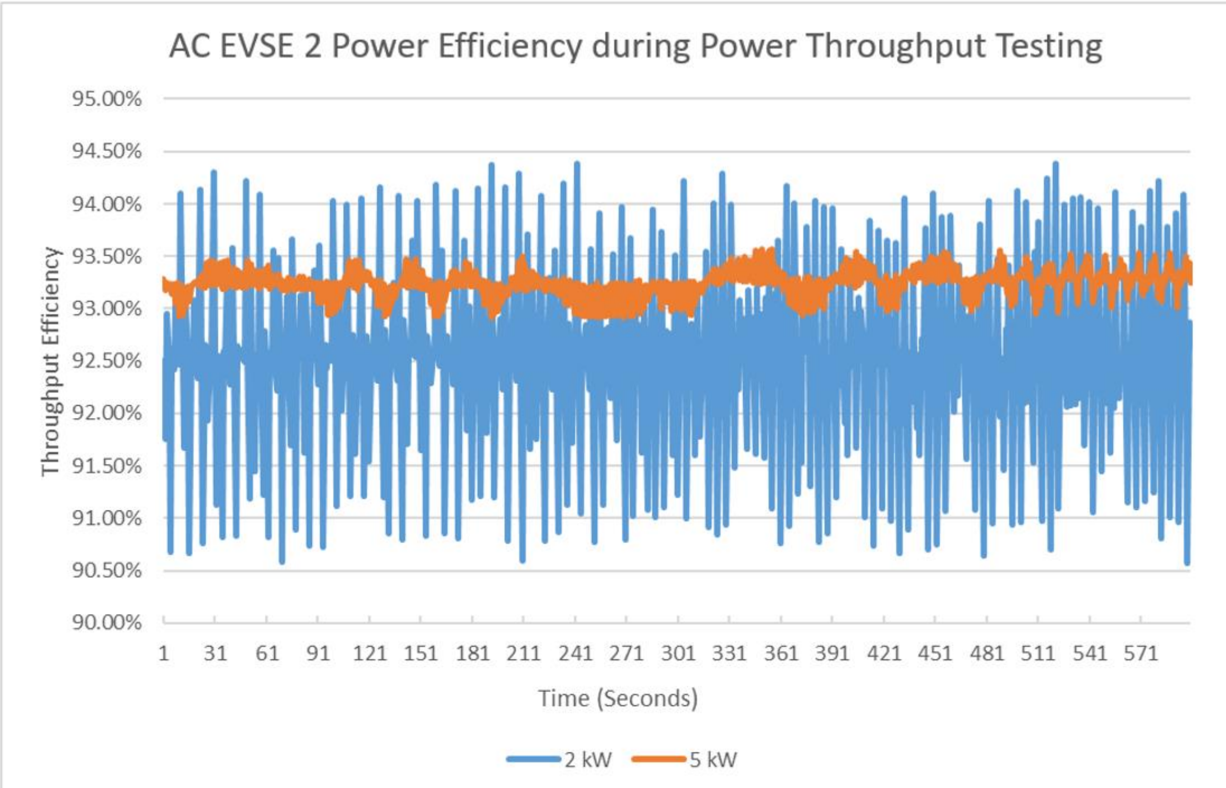

Figure 7: AC EVSE 2 power efficiency during power throughput testing.

Source: CLTC.

AC EVSE 3

Table 14 indicates that AC EVSE 3 delivered efficiencies between 92.0 percent and 92.6 percent, with average power close to 6.9 kW under default charging conditions. Results were within the same band as the other AC units.

Table 14: AC EVSE 3 SOC testing scenario results.

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
1	10.01%	13.15%	6946.06	92.00%

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
2	24.96%	27.82%	6934.76	92.32%
3	74.45%	77.08%	6949.11	92.56%
4	N/A*	N/A*	N/A*	N/A*

*Range exceeded testbed SOC capabilities.

Source: CLTC.

SOC testing in Figure 8 demonstrated efficiency starting at 92.0 percent at 10 percent SOC and increasing slightly to 92.6 percent at 75 percent SOC. The overall trend was stable.

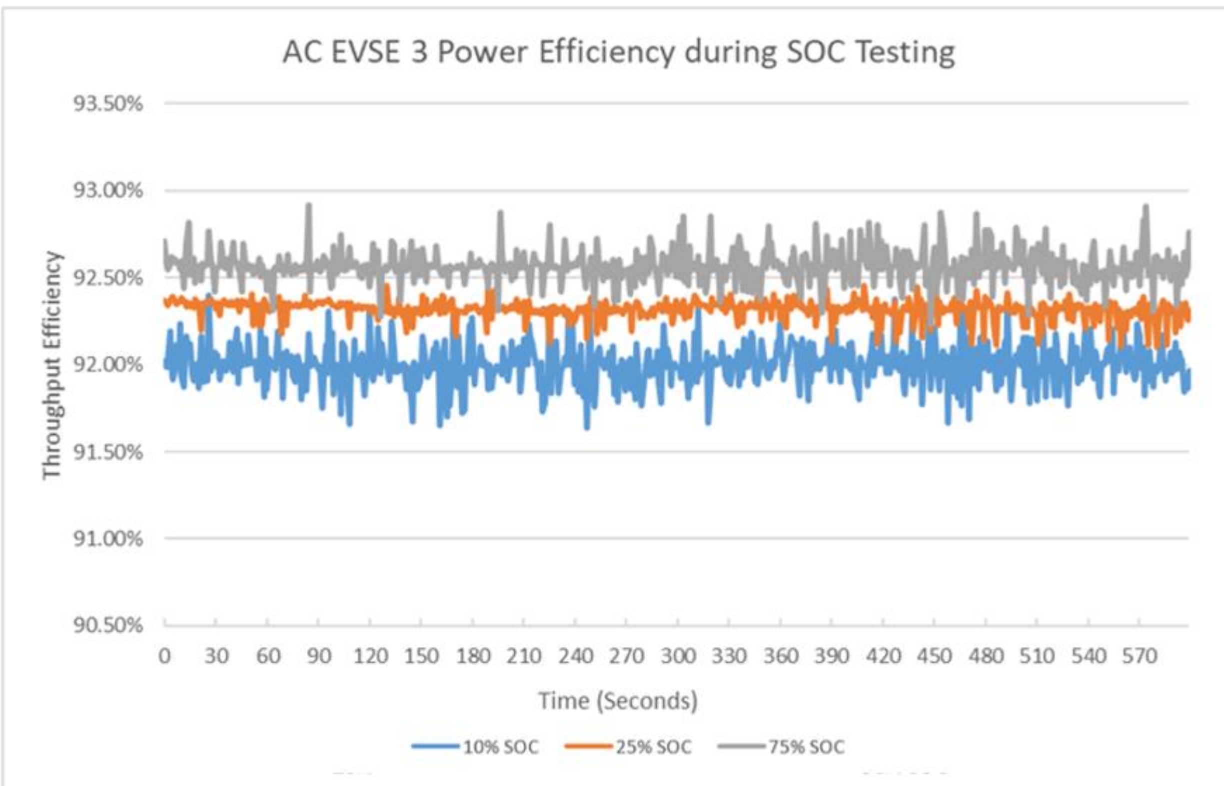

Figure 8: AC EVSE 3 power efficiency during SOC testing.

Source: CLTC.

Power throughput results in Table 15 show 90.7 percent efficiency at approximately 2.1 kW and 92.9 percent efficiency at approximately 5.5 kW. This represented the largest gain among the AC units as throughput increased.

Table 15: AC EVSE 3 power throughput testing scenario results.

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
5	10.89%	11.86%	2129.68	90.71%
6	10.07%	12.60%	5459.00	92.90%
7	N/A*	N/A*	N/A*	N/A*

*Range exceeded EVSE power capabilities.

Source: CLTC.

The graph in Figure 9 shows variability patterns similar to the other AC units. The greatest scatter occurred at approximately 2 kW, similar to AC EVSE 1, which could indicate the system struggling to maintain lower power targets, with efficiency roughly trending upward by roughly 1 percent. At approximately 5 kW, variability was lower, but still greater than at default power, with efficiency trending upward by about 0.25 percent.

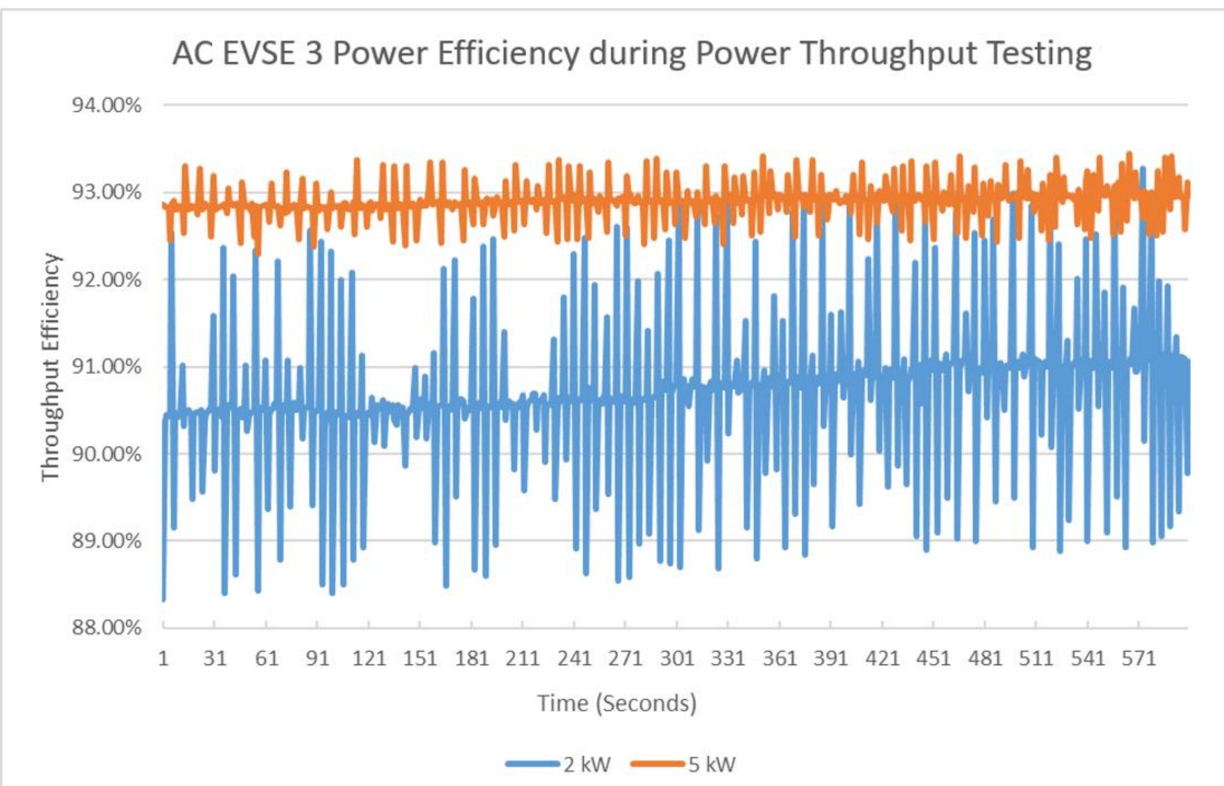

Figure 9: AC EVSE 3 power efficiency during power throughput testing.

Source: CLTC.

AC EVSE 4

Table 16 shows that AC EVSE 4 displayed slightly lower average power of approximately 3.4 kW, with efficiencies ranging from 92.51 percent to 93.10 percent. Despite the lower throughput due to system design limitations, efficiency values remained competitive with the other AC units.

Table 16: AC EVSE 4 SOC testing scenario results.

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
1	9.93%	11.56%	3439.79	92.51%
2	24.87%	26.42%	3455.79	92.93%
3	75.04%	76.37%	3463.66	93.10%
4	N/A*	N/A*	N/A*	N/A*

*Range exceeded testbed SOC capabilities

Source: CLTC

SOC tests presented in Figure 10 show efficiency as low as 92 percent at 10 percent SOC and increasing slightly to maximum 94 percent at 75 percent SOC. The trend was overall flat but had significant peaks of variability during all test cases, indicating that lower power levels may be harder to maintain or the electrical architecture of the lower power charger may be less sophisticated compared to the higher power throughput—and higher cost—EVSEs.

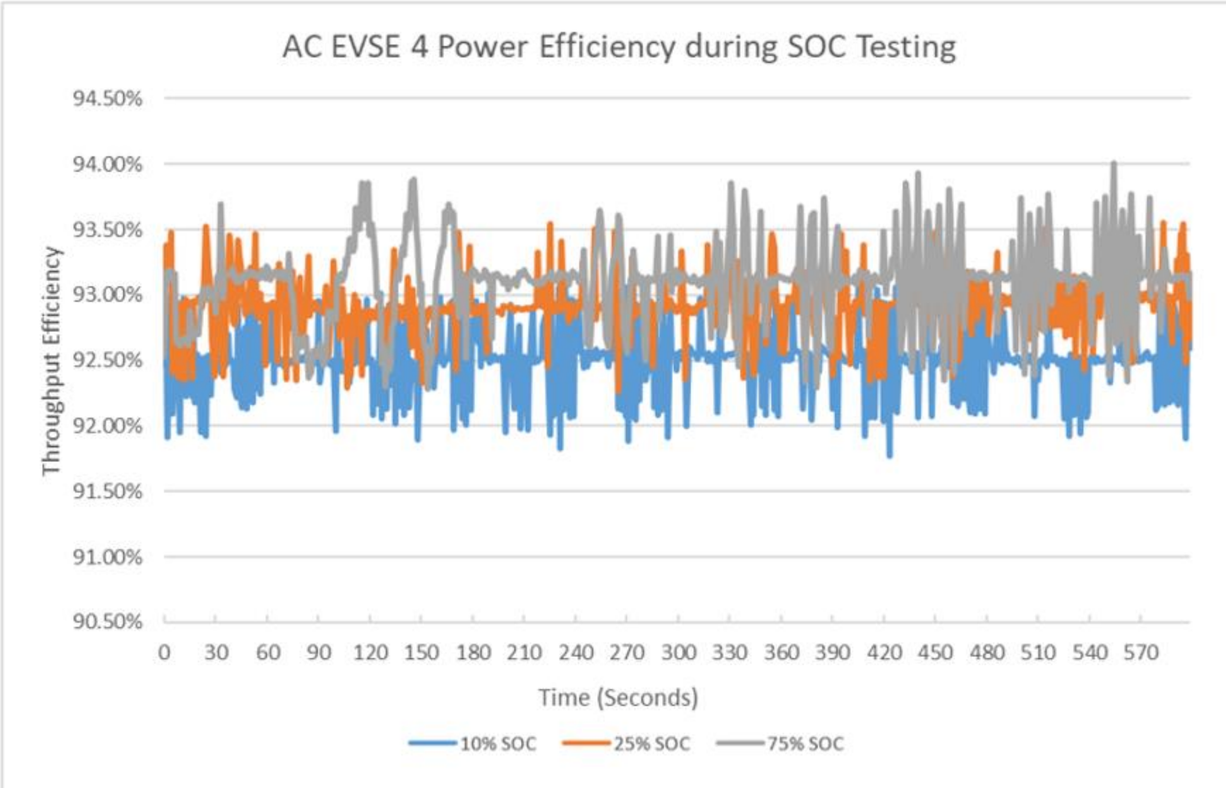

Figure 10: AC EVSE 4 power efficiency during SOC testing.

Source: CLTC.

In the power throughput tests, Table 17 shows 93.1 percent efficiency at approximately 2.2 kW. Higher-load data was not possible to collect due to overall system maximum power throughput.

Table 17: AC EVSE 4 power throughput testing scenario results.

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
5	9.88%	10.87%	2172.76	93.05%
6	N/A*	N/A*	N/A*	N/A*
7	N/A*	N/A*	N/A*	N/A*

*Range exceeded EVSE power capabilities.

Source: CLTC.

As seen in Figure 11, the power curve was generally stable, with no significant increase or decrease across the tested range. However, variability was the highest among the AC units, with efficiency values spanning a range of approximately 3 percent.

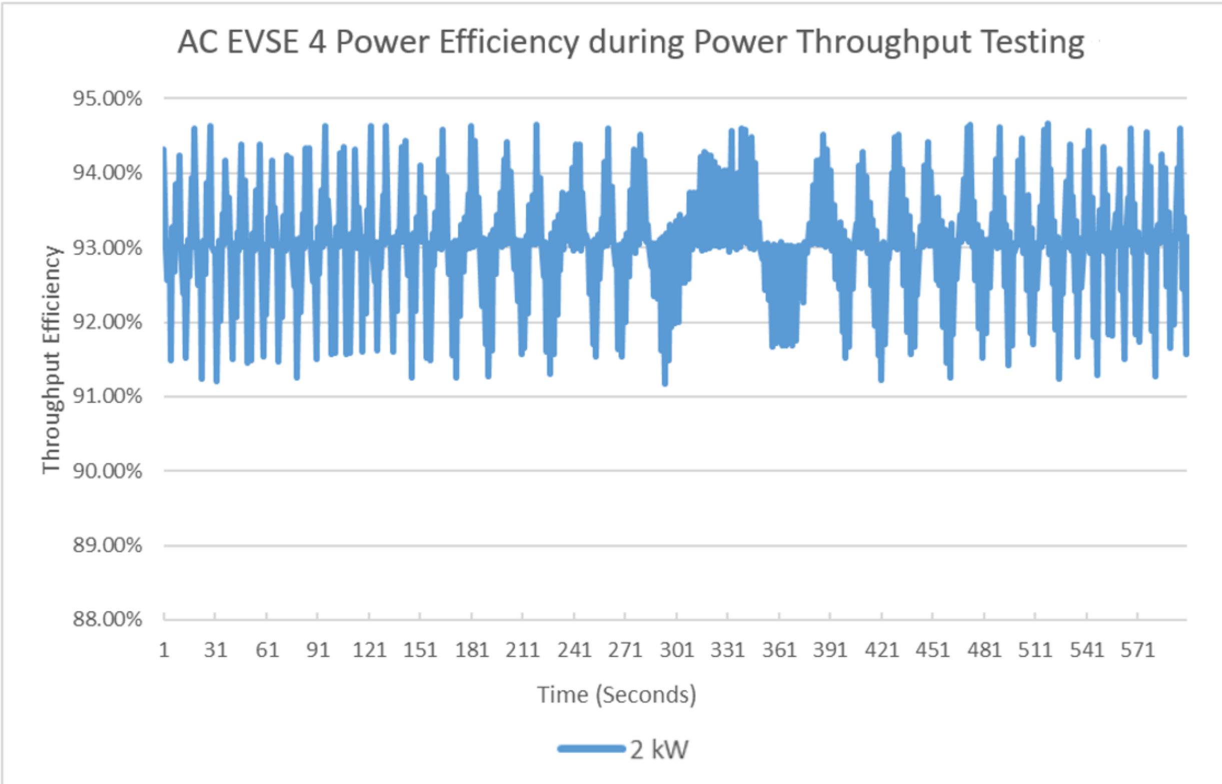

Figure 11: AC EVSE 4 power efficiency during power throughput testing.

Source: CLTC.

DC EVSE 1

As summarized in Table 18, DC EVSE 1 delivered average efficiencies between 92.10 percent and 93.12 percent, with power values ranging from 6.4 kW to 7.8 kW across SOC conditions. The team found that DC EVSE 1 underperformed with its specification (Table 6) and was unable to achieve the claimed 10 kW power level.

Table 18: DC EVSE 1 SOC testing scenario results.

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
1	10%*	10%*	6432.72	92.10%

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
2	25% *	25% *	6720.04	92.28%
3	75% *	75% *	7579.27	93.01%
4	90% *	90% *	7832.57	93.12%

*SOC in DC testbed was emulated and remained constant.

Source: CLTC.

SOC testing in Figure 12 showed efficiency beginning at 92.1 percent at 10 percent SOC before increasing to 93.1 percent at 90 percent SOC. During testing, trends for each scenario remained steady; however, there is a significant gap across test scenarios, especially between 25 percent and 75 percent. This indicates SOC and targeted power play a significant role in efficiency.

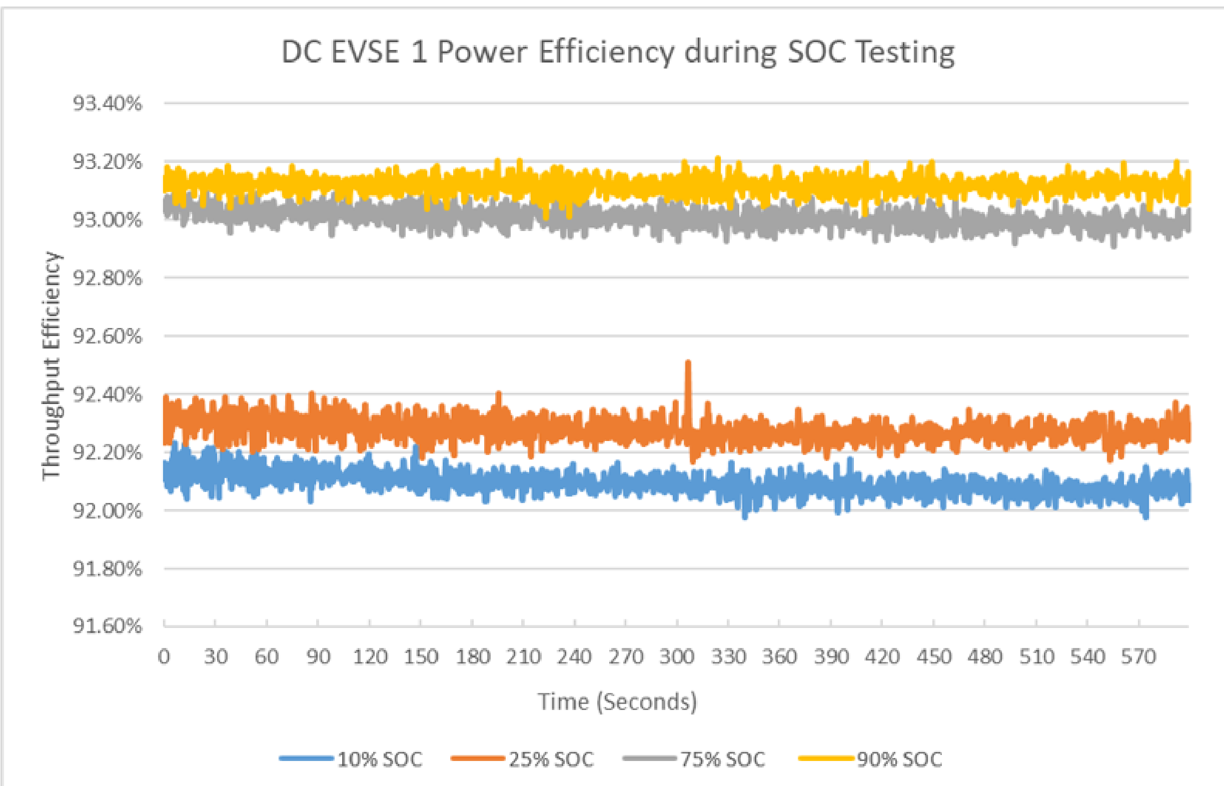

Figure 12: DC EVSE 1 power efficiency during SOC testing.

Source: CLTC

For power throughput testing, Table 19 reports efficiency values of 90.4 percent at 2.1 kW and 92.4 percent at 5.2 kW. These results show a clear gain in performance with higher throughput. Interestingly, scenario 6 had a slightly higher power efficiency than the default power strategy in scenario 1, indicating that when it comes to efficiency, the default power delivery may not be the most optimal in every system.

Table 19: DC EVSE 1 power throughput testing scenario results.

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
5	10%**	10%**	2105.02	90.36%
6	10%**	10%**	5158.13	92.44%
7	10%**	10%**	N/A*	N/A*

*Range exceeded EVSE power capabilities

**SOC in DC testbed was emulated and remained constant

Source: CLTC

Figure 13 shows flat efficiency trends across the tested power ranges. Variability was slightly higher at 2.1 kW, but it remained more consistent in comparison to AC EVSE results at the same condition. At higher loads, the curve remained stable with minimal scatter.

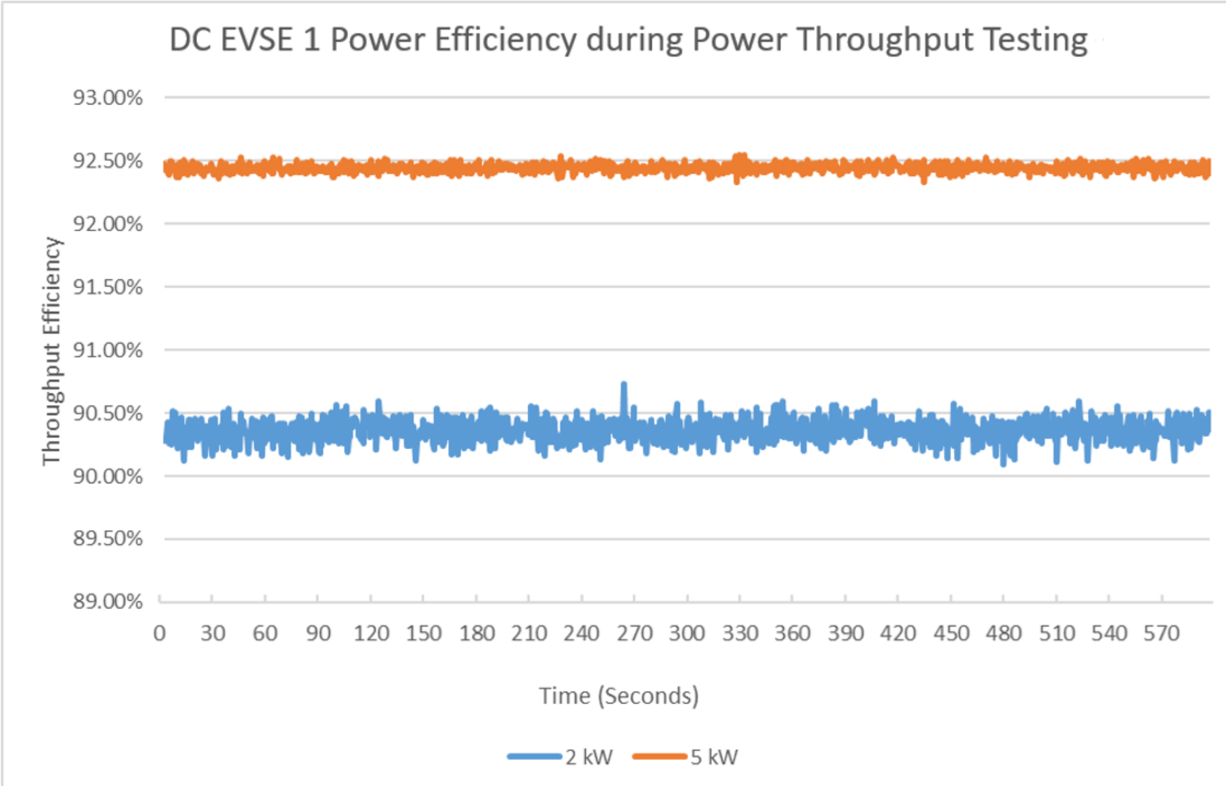

Figure 13: DC EVSE 1 power efficiency during power throughput testing.

Source: CLTC

DC EVSE 2

As shown in Table 20, DC EVSE 2 achieved average efficiencies between 95.42 percent and 95.71 percent, with default power ranging from 9.7 kW to 11.8 kW across SOC levels. These results indicate higher efficiency values than those observed in DC EVSE 1.

Table 20: DC EVSE 2 SOC testing scenario results.

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
1	10%*	10%*	9697.69	95.42%
2	25% *	25% *	10091.15	95.49%
3	75% *	75% *	11397.60	95.68%

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
4	90% *	90% *	11787.45	95.71%

*SOC in DC testbed was emulated and remained constant

Source: CLTC

The SOC data presented in Figure 14 showed efficiency holding steady, with values of 95.4 percent at 10 percent SOC and 95.7 percent at 90 percent SOC. The trend was stable across the entire charging cycle.

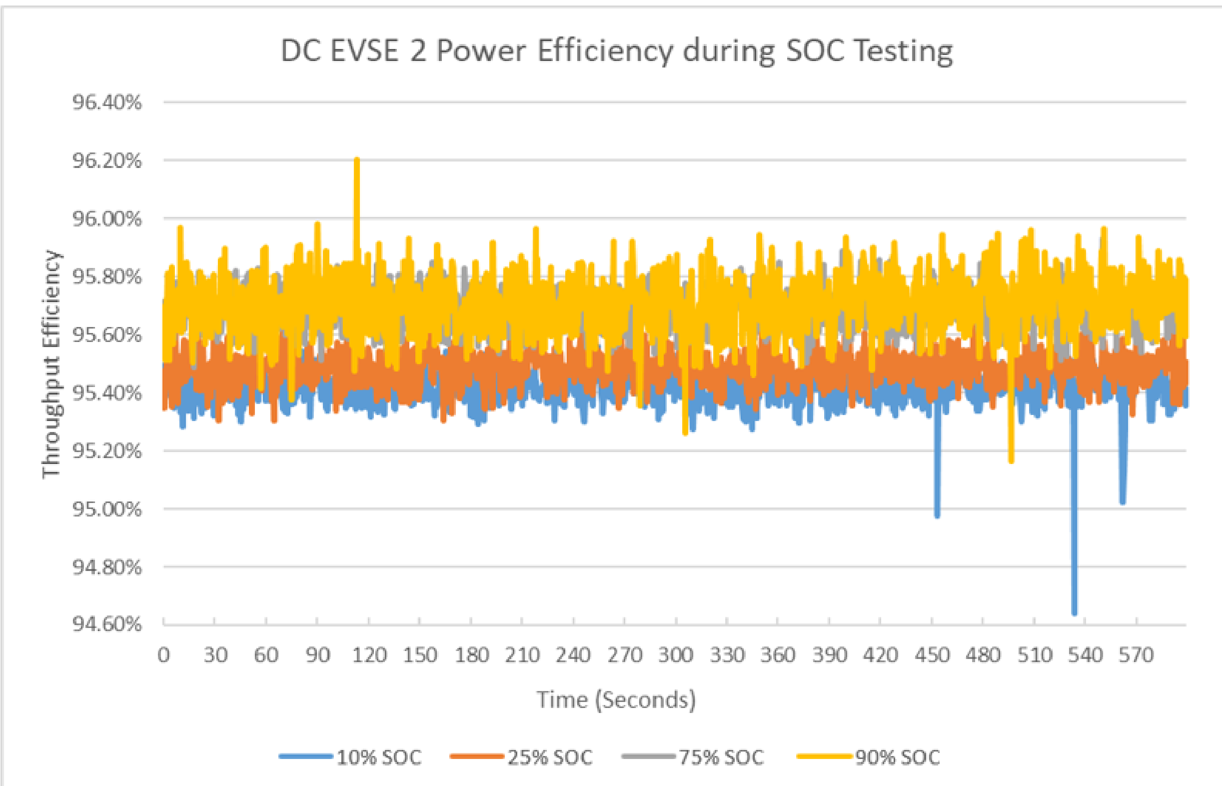

Figure 14: DC EVSE 2 power efficiency during SOC testing.

Source: CLTC

As presented in Table 21, power throughput testing reported 88.55 percent efficiency at approximately 2.1 kW, 92.73 percent at 5.0 kW, and 95.48 percent at 10 kW. These results highlight significant improvement as throughput increased.

Table 21: DC EVSE 2 power throughput testing scenario results.

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
5	10%*	10%*	2138.13	88.55%
6	10%*	10%*	4973.09	92.73%
7	10%*	10%*	10028.58	95.48%

*SOC in DC testbed was emulated and remained constant

Source: CLTC

The power curve remained flat overall, as shown in Figure 15, and efficiency stayed consistent across the tested range. Even in this condition, the team observed significantly less scatter than in the AC units and DC EVSE 1.

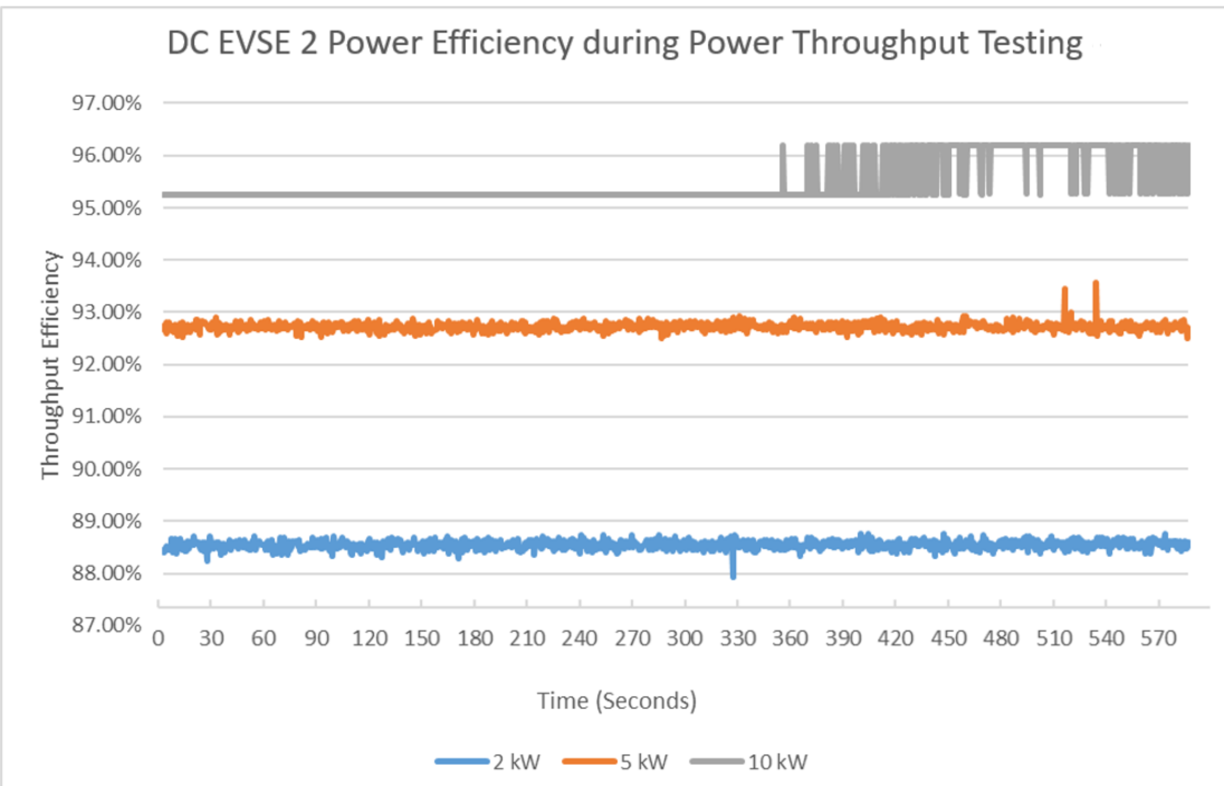

Figure 15: DC EVSE 2 power efficiency during power throughput testing.

Source: CLTC

DC EVSE 3

Table 22 shows DC EVSE 3—with average efficiencies between 96.16 percent and 96.70 percent—paired with power ranging from 10.0 kW to nearly 12.0 kW. These values represent higher performance than either DC EVSE 1 or DC EVSE 2.

Table 22: DC EVSE 3 SOC testing scenario results.

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
1	10%*	10%*	10000.20	96.16%
2	25% *	25% *	10404.45	96.41%
3	75%*	75% *	11741.30	96.69%
4	90% *	90% *	11976.35	96.70%

*SOC in DC testbed was emulated and remained constant

Source: CLTC

SOC testing in Figure 16 confirmed stable results, starting at 96.2 percent at 10 percent SOC and reaching 96.7 percent at 90 percent SOC. Efficiency remained consistently high across the SOC range, but efficiency variability was noticeably stable at low SOC conditions before the system logic took a number of seemingly intended efficiency steps; the team believes this could be the EVSE's attempt to deploy battery health optimization strategies intended to prolong vehicle life.

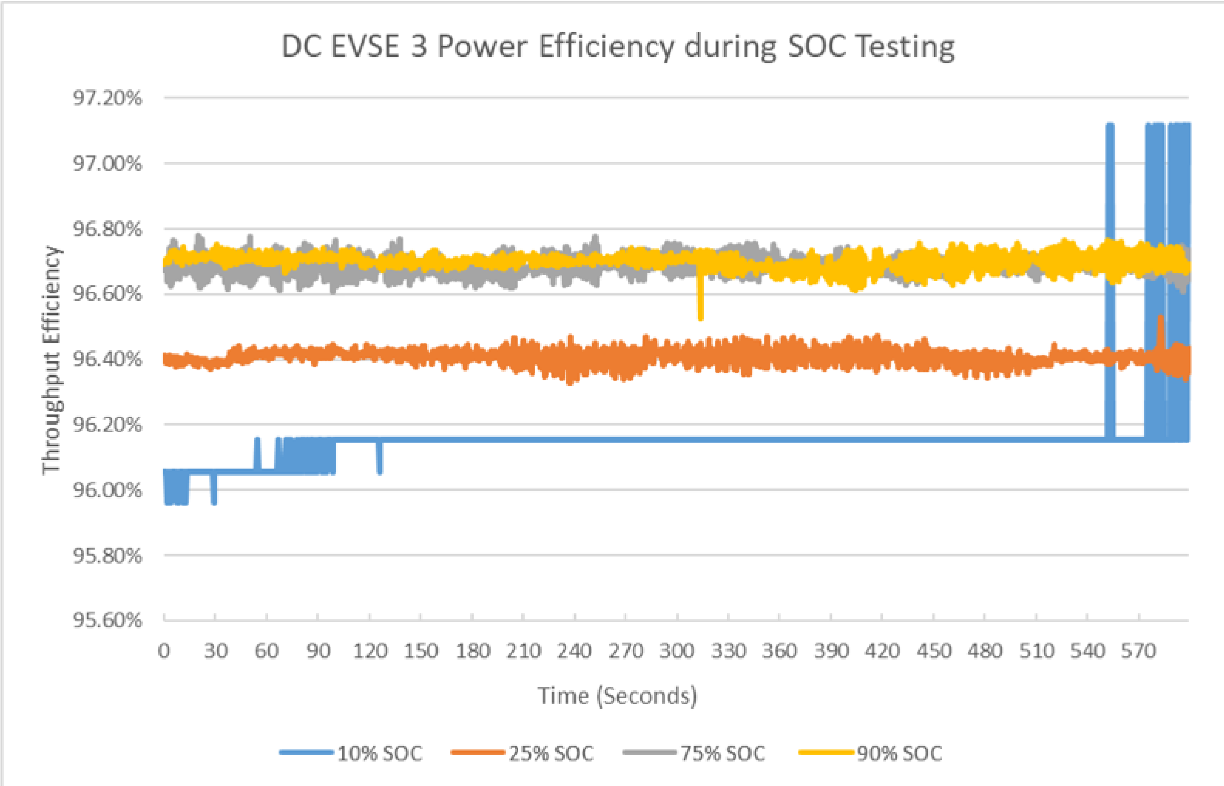

Figure 16: DC EVSE 3 power efficiency during SOC testing.

Source: CLTC

Power throughput test results in Table 23 included 92.68 percent at 2.0 kW, 95.73 percent at 4.8 kW, and 96.16 percent at 10 kW. Performance increased steadily as throughput levels rose.

Table 23: DC EVSE 3 power throughput testing scenario results.

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
5	10%*	10%*	2019.67	92.68%
6	10%*	10%*	4809.23	95.73%
7	10%*	10%*	10000.20	96.16%

*SOC in DC testbed was emulated and remained constant

Source: CLTC

The graph in Figure 17 displayed a flat trend across all tested loads with minor variability. Overall results showed that at lower power levels, efficiency significantly dropped but remained comparable to the AC units.

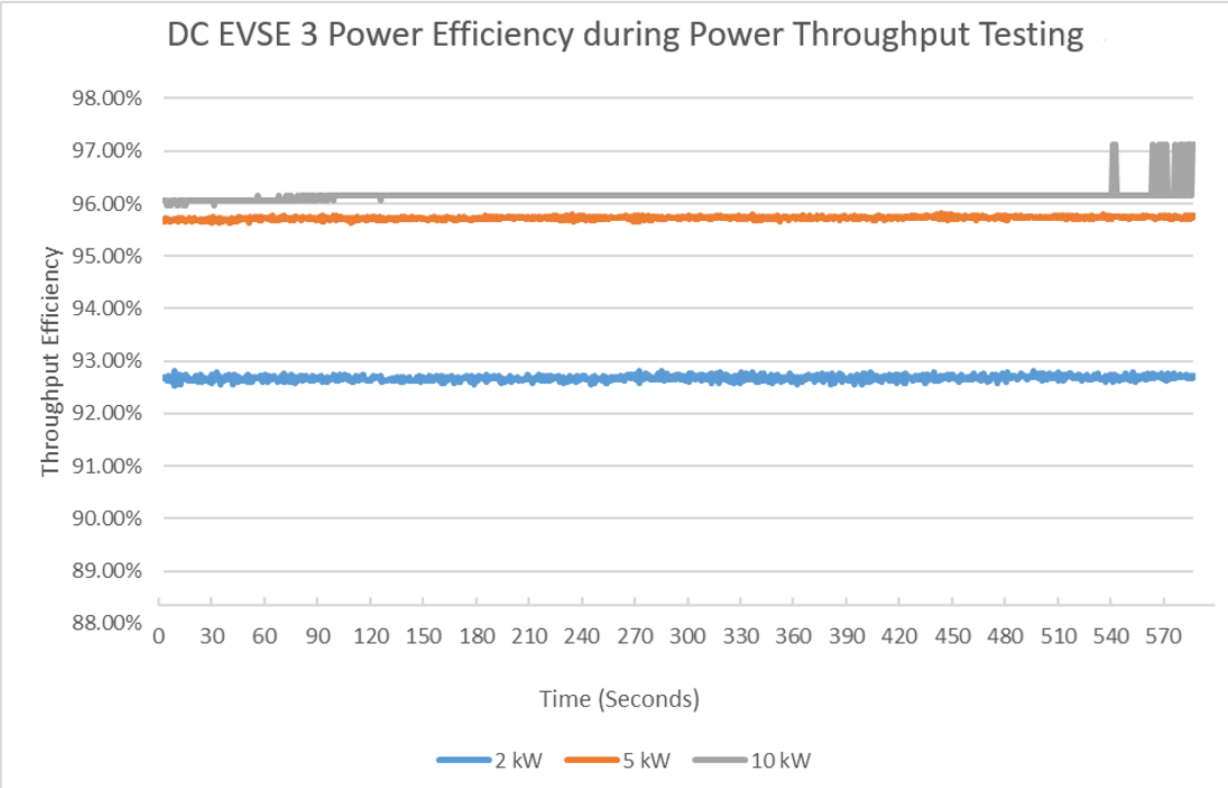

Figure 17: DC EVSE 3 power efficiency during power throughput testing.

Source: CLTC

DC EVSE 4

Lastly, Table 24 shows DC EVSE 4 achieved average efficiencies between 95.57 percent and 96.12 percent, with power ranging from 10.1 kW to 12.0 kW. These results are broadly consistent with DC EVSE 2 and slightly below the values recorded for DC EVSE 3.

Table 24: DC EVSE 4 SOC testing scenario results.

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
1	10%*	10%*	10055.17	95.57%

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
2	25% *	25% *	10401.86	95.69%
3	75% *	75% *	11702.21	96.06%
4	90% *	90% *	11975.86	96.12%

*SOC in DC testbed was emulated and remained constant

Source: CLTC

SOC testing in Figure 18 indicated efficiency values of 95.6 percent at 10 percent SOC and 96.1 percent at 90 percent SOC. The curve remained flat across the test scenarios with some variance; however, at 25% SOC there was a notable amount of additional outliers present.

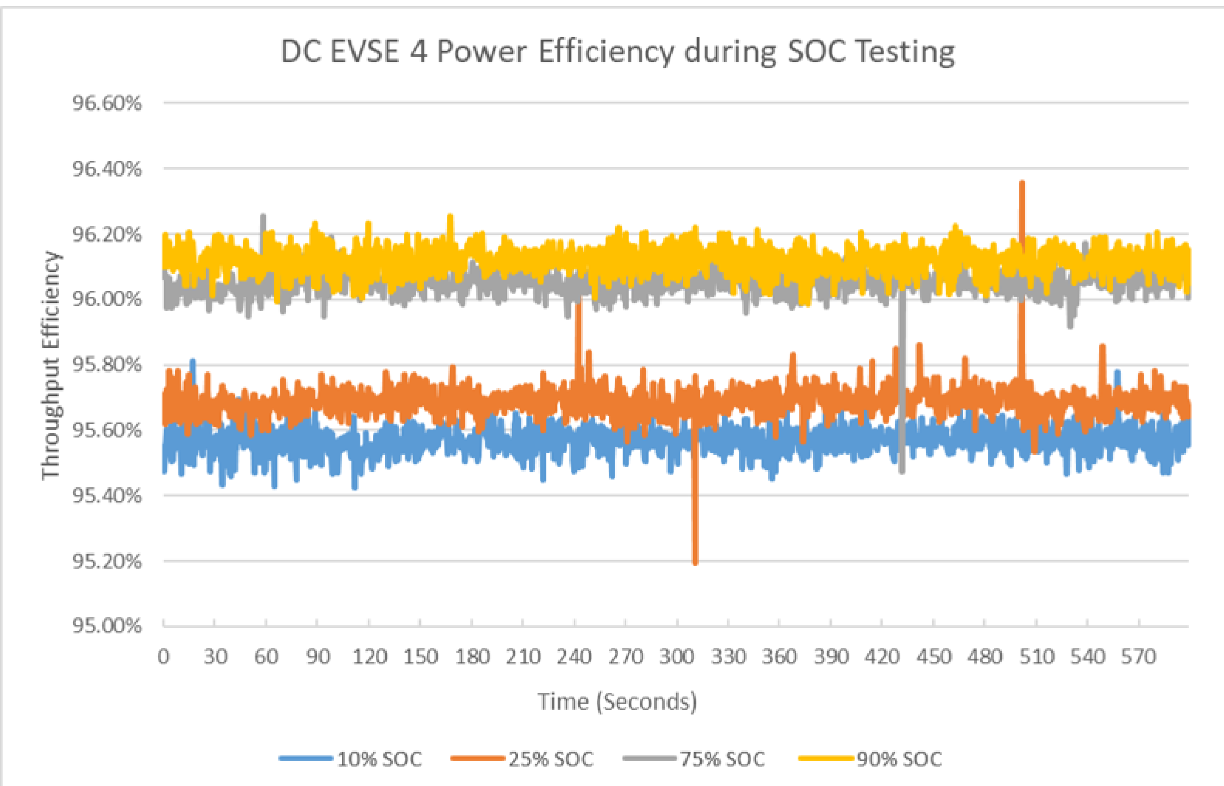

Figure 18: DC EVSE 4 power efficiency during SOC testing.

Source: CLTC

Power throughput testing in Table 25 reported 88.76 percent efficiency at 1.8 kW, 94.62 percent at 5.4 kW, and 95.57 percent at 10 kW. Results showed a pronounced efficiency increase between low- and mid-load operation.

Table 25: DC EVSE 4 power throughput testing scenario results.

Scenario	Start SOC	End SOC	Power (W)	Power Conservation Efficiency
5	10%*	10%*	1836.21	88.76%
6	10%*	10%*	5436.56	94.62%
7	10%*	10%*	10055.17	95.57%

*SOC in DC testbed was emulated and remained constant

Source: CLTC

In Figure 19, the power curve was stable across the tested range, showing no noticeable upward or downward trends. Variability increased slightly at 2 kW but was still substantially lower than the variability recorded in the AC tests.

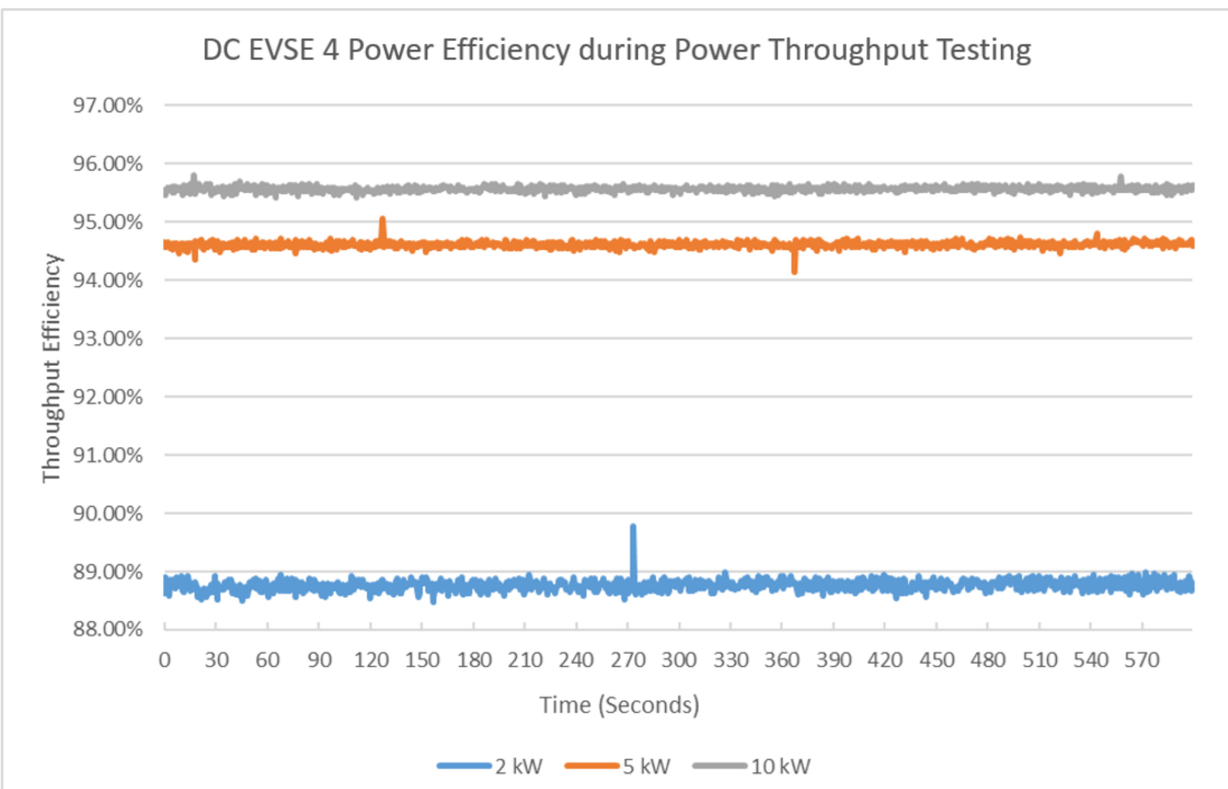

Figure 19: DC EVSE 4 power efficiency during power throughput testing.

Source: CLTC

Analysis: Phase 1

Across all test scenarios, the difference between AC and DC EVSE performance was clear at default power levels. AC chargers consistently operated in the 91 percent to 93 percent efficiency range, with only modest variation across scenarios and units. Most DC chargers sustained significantly higher efficiencies, frequently in the 95 to 97 percent range, particularly at mid- and high-load conditions. However, the team noted several instances of suboptimal performance, especially during the 2 kW power testing—likely due to the DC charger struggling to maintain a charging speed significantly different than its default. As shown in Figure 20, the AC systems clustered at power levels between 2 kW and 7 kW, while DC systems extended to 10 kW to 12 kW and maintained superior efficiency at those higher throughput levels.

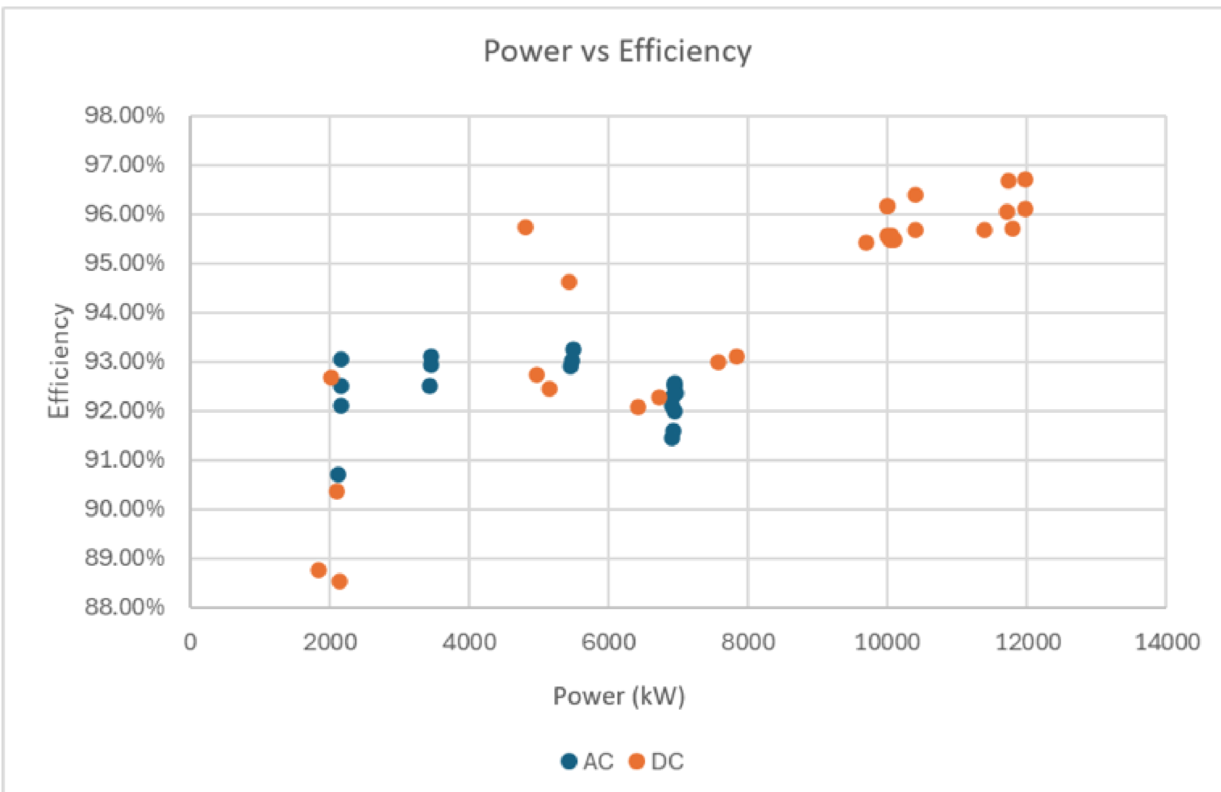

Figure 20: Efficiency vs. power for all tested units.

Source: CLTC

While DC charging generally outperformed AC, the team observed some unit-specific deviations. In scenarios 1 through 4, DC EVSE 1 performed closer to the AC units, with efficiencies in the low 90s rather than the higher range typical of the other DC systems. DC EVSE 1 had the lowest maximum power of the DC units at 10 kW—and had a significantly lower price—indicating performance could be due to overall design choices. In test scenario 5, which targeted 2 kW power targets, DC EVSE 2 and DC EVSE 4 recorded the lowest efficiencies of the group, falling below 89 percent. This indicates that DC systems, although well-suited for higher power delivery, can lose efficiency when constrained to very low power targets. Notably, these conditions do not represent default charging strategies for DC equipment.

DC EVSE 3, which is the only ENERGY STAR–rated DC product, notably outperformed all other products in six of the seven tests. That said, ENERGY STAR-rated AC products (AC EVSE 1 and AC EVSE 3) performed in line with other units and were regularly outperformed by AC EVSE 4 in terms of efficiency; however, that does not account for the fact that AC EVSE 4 targets much lower power levels (3.8 kW maximum) while the ENERGY STAR-rated AC EVSE products are 12 kW and 7.7 kW.

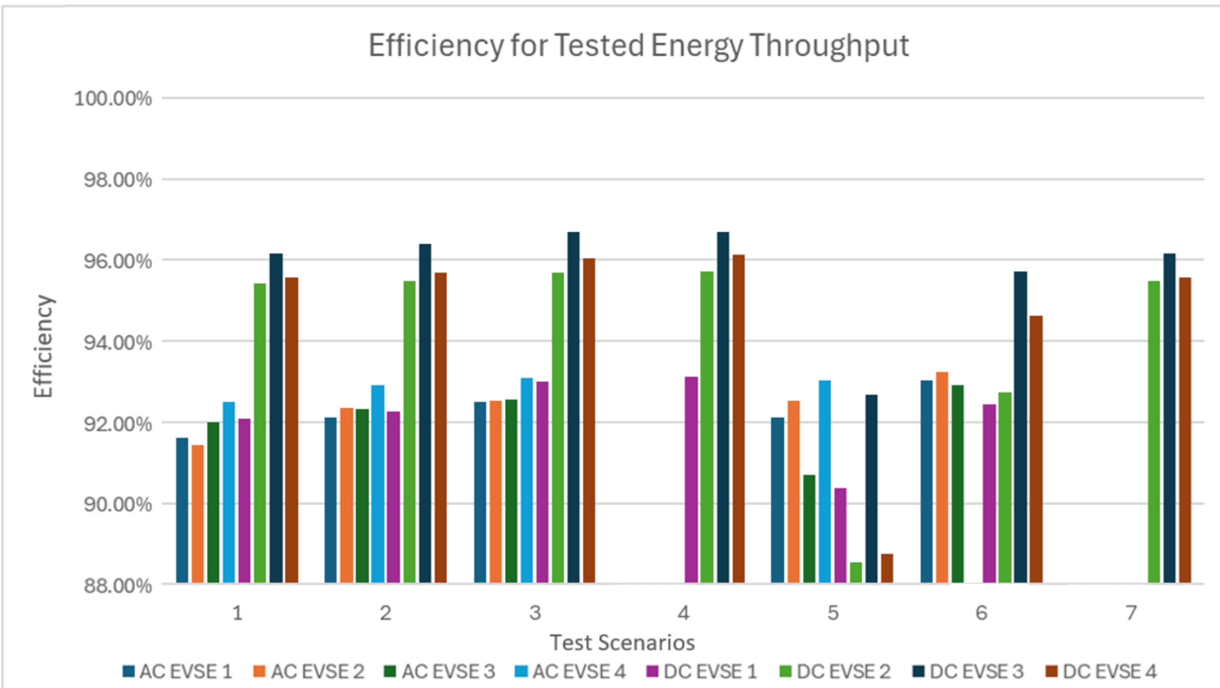

Figure 21: Efficiency of tested units across all testing scenarios.

Source: CLTC

Using the average of the AC and DC charging efficiencies in the default power scenarios of 92.33 percent and 95.14 percent, respectively, the team estimated the annual energy consumption for EV charging. Assuming an EV travel efficiency of 4 miles per kilowatt-hour (kWh) and an average annual mileage of 11,409 miles—reflecting the average for California drivers (Federal Highway Administration, 2025)—AC charging would consume approximately 3,089 kWh per year, while DC charging would require about 2,998 kWh per year.

This translates to a potential savings of 91.24 kWh per EV annually when switching from AC to DC charging. However, savings could be hampered by inadequate chargers, as DC EVSE 1's performance was comparably underwhelming and there is an overall recommendation to source ENERGY STAR–certified hardware. With California's current light-duty, zero-emission vehicle fleet totaling 1,899,831 vehicles (California Energy Comision, n.d.), the aggregate savings could reach approximately 173 gigawatt-hour (GWh) per year. This figure is expected to grow significantly as California continues to expand its EV fleet under the state's net-zero carbon emissions initiative.

In addition to energy savings, these reductions directly translate to avoided greenhouse gas emissions when using grid-supplied electricity. Applying California's current average grid emissions factor of 80.55 grams of carbon-dioxide equivalent per megajoule (gCO_2e/MJ)—equivalent to 290 gCO_2e per kWh calculated in the Low Carbon Fuel Standard Annual Updates published by the California Air Resources Board (California Air Resources Board, n.d.)—the total greenhouse gas savings from switching all vehicles to DC charging would amount to approximately 50,269,075 kilograms of CO_2e annually. This estimate assumes all energy savings would have otherwise been sourced from the grid and does not account for any contributions from behind-the-meter solar or other low-carbon sources.

The team calculated expected customer savings from California's investor-owned utilities using the preferred EV time-of-use (TOU) rates provided by Pacific Gas & Electric Company (PG&E), Southern California Edison (SCE), and San Diego Gas & Electric (SDG&E) in Figure 22 through Figure 24 (SCE, n.d.) (SDGE, n.d.) (PG&E, n.d.) The analysis assumes that all EV charging occurs during the lowest-cost, off-peak period, from 12:00 a.m. to 6:00 a.m. The resulting annual cost of EV charging under both AC and DC scenarios is shown below and detailed further in Table 26.

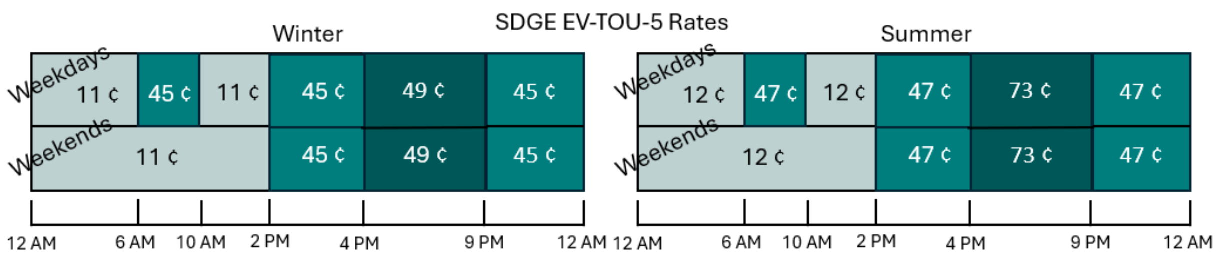

Figure 22: SDG&E EV-TOU-5 rate structure.

Source: SDG&E

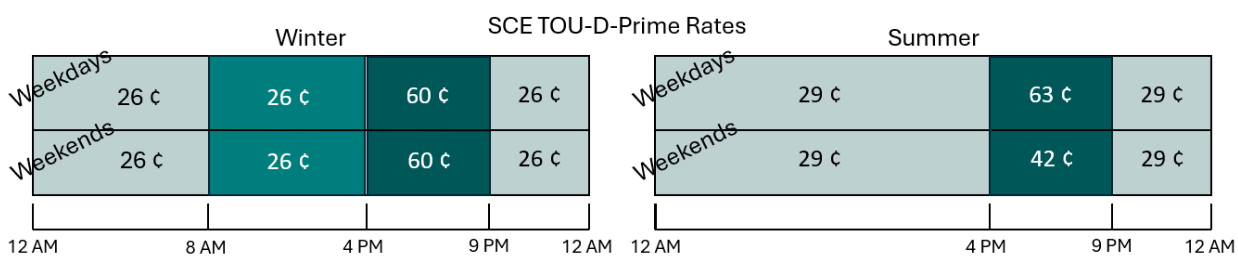

Figure 23: SCE TOU-D-Prime rate structure.

Source: SCE

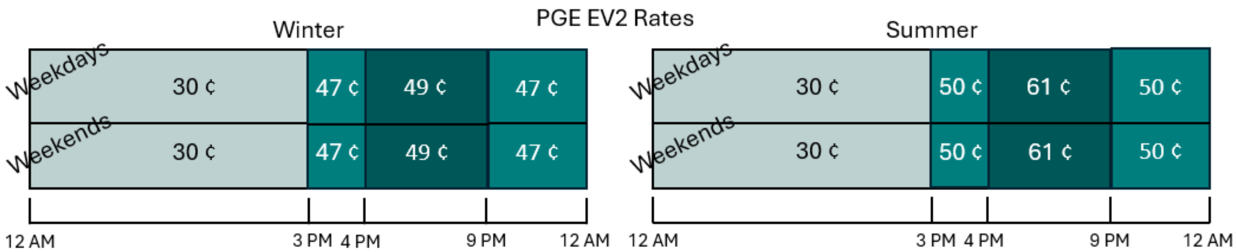

Figure 24: PG&E EV2 rate structure.

Source: PG&E

Table 26: Annual yearly costs for AC and DC charging.

Utility	$/Year for AC EVSE	$/Year for DC EVSE
PG&E	$ 927.87	$ 900.46
SCE	$ 842.04	$ 817.17
SDG&E	$ 358.15	$ 347.57

Source: CLTC

While DC chargers continue to offer modest annual energy cost savings over AC systems—ranging from $10.58 to $27.41 per year, depending on the utility TOU rate—upfront hardware costs remain the key barrier to adoption. From the identified EVSE systems the project team found:

- Residential AC Level 2 EVSE units average $399.39, making them the most cost-effective option available today.
- Commercial AC EVSE units are substantially more expensive, with an average cost of $3,029.17.
- DC EVSE units in this analysis are largely mixed-use or commercial-rated, with no truly residential-focused models. These units average $9994.50, though some mixed-use systems cost as little as $4,500.

It is important to note that DC EVSE remains a less mature product category, especially in the residential and small commercial space. As technology evolves and manufacturing scales, unit costs are expected to decline, reducing the payback period and improving cost effectiveness. The emergence of more affordable, lower-power DC options could shift this balance significantly. Moreover, targeted incentive programs could lower financial barriers and accelerate the deployment of more efficient DC systems.

Results: Phase 2

To supplement the discrete SOC testing performed during Phase 1, the team selected a subset of previously evaluated EVSE systems for extended vehicle charging evaluation. Two AC EVSE units (AC EVSE 1 and AC EVSE 2) and two DC EVSE units (DC EVSE 2 and DC EVSE 4) were tested using a vehicle-based charging configuration over an expanded charging session, spanning approximately 10 percent to 80 percent battery SOC. We selected these systems to represent a subset of the equipment evaluated during Phase 1 while maintaining similar power classes within each charging category.

For Phase 2 testing, the team reacquired the same vehicle used during Phase 1 and integrated it into the testbed. At the time of Phase 2 testing, the vehicle had accumulated approximately 1,000 additional miles relative to the Phase 1 evaluation. This increase represents a small fraction of the vehicle's total mileage and is not expected to impact charging performance during the evaluation. Although the same vehicle platform and instrumentation approach were used, the Phase 2 results should not be interpreted as a direct comparison to the Phase 1 discrete SOC evaluations. The Phase 1 testing evaluated charger performance at fixed operating points, whereas the Phase 2 testing evaluated charger behavior continuously throughout a representative charging session. Consequently, the two datasets provide complementary perspectives on charging performance rather than directly comparable efficiency measurements.

To provide additional context within the continuous charging datasets, efficiency values are reported at nominal SOC values of 10 percent, 25 percent, and 75 percent. These values are not intended as direct comparisons to the discrete SOC results presented in Phase 1. Rather, they provide representative snapshots of charging performance at selected points throughout the charging session. Because SOC values were continuously changing during testing, the reported efficiencies represent averaged measurements within the target SOC, with half-second data pull rates.

Two efficiency metrics are presented throughout the Phase 2 evaluation: EVSE efficiency represents the charging equipment's efficiency, which the team calculated using measurements collected at the EVSE input and output, and full-path efficiency represents the overall charging pathway from grid input to energy delivered to the vehicle battery. As a result, full-path efficiency incorporates losses associated with the charging equipment, vehicle charging system, and battery charging process, while EVSE efficiency isolates the performance of the charging equipment itself.

AC EVSE 1

AC EVSE 1 completed the charging event from approximately 10 percent to 80 percent SOC in 6.81 hours; Figure 25 shows the measured charging power throughout the session. AC EVSE 1 maintained a near-constant charging power of approximately 7.2 kW across the evaluated SOC range, with only minor short-duration fluctuations observed during the test. No significant power derating or charging interruptions were observed.

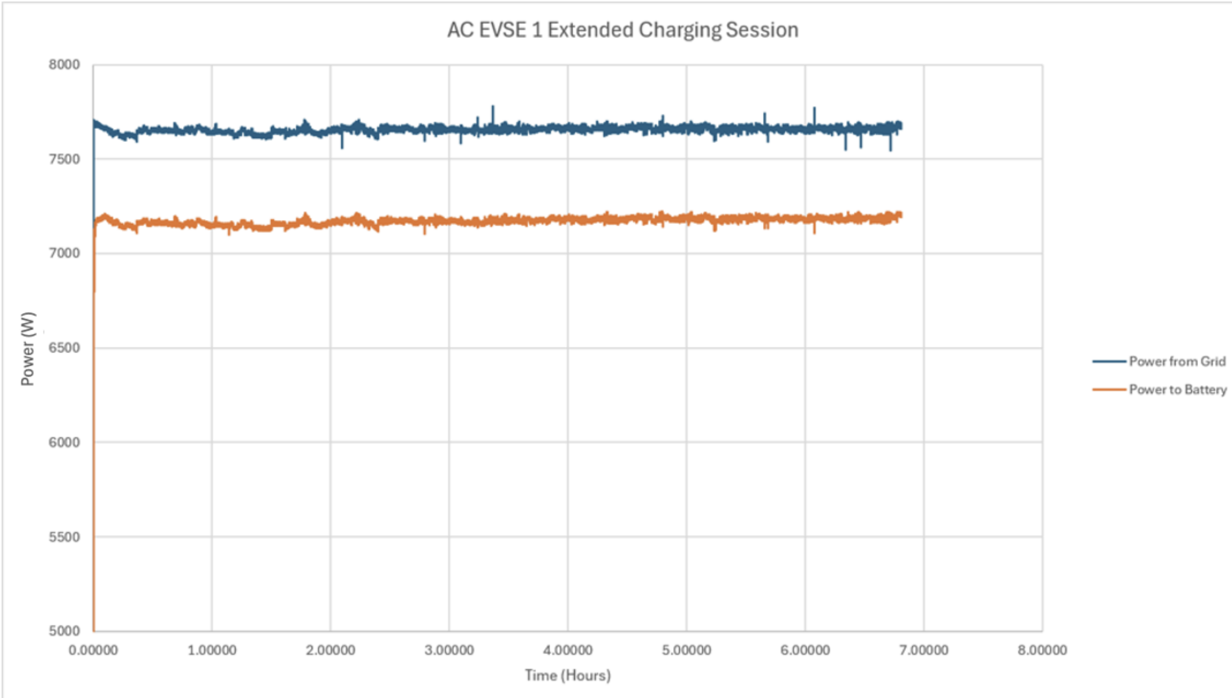

Figure 25: AC EVSE 1 power for extended charge session.

Source: CLTC

Figure 26 presents the measured efficiency profile for AC EVSE 1 throughout the charging event. Full-path efficiency remained highly stable across the evaluated charging range, averaging approximately 93.7 percent. At the target SOC values used throughout this report, measured full-path efficiency was 93.8 percent at 10 percent SOC, 93.5 percent at 25 percent SOC, and 93.8 percent at 75 percent SOC. The limited variation across the charging session indicates consistent energy transfer performance from the utility interface through the vehicle battery system.

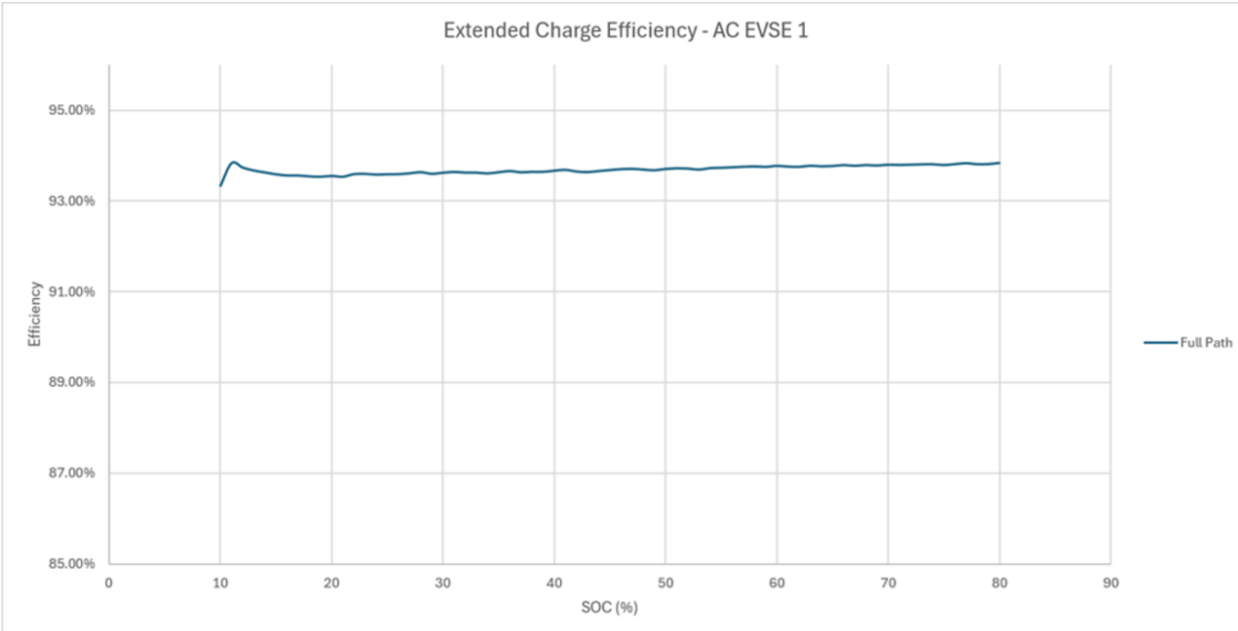

Figure 26: AC EVSE 1 efficiency for extended charge session.

Source: CLTC

Measured EVSE efficiency remained near constant throughout the charging event and exceeded 99 percent, indicating very low conversion losses within the charging equipment itself. Consistent with the observations from Phase 1, the majority of charging losses were associated with the vehicle charging system rather than the EVSE.

AC EVSE 2

AC EVSE 2 completed the charging event from approximately 10 percent to 80 percent SOC in 6.63 hours. Figure 27 shows the measured charging power throughout the session. As with AC EVSE 1, AC EVSE 2 maintained a near-constant charging power of approximately 7.2 kW throughout the charging event.

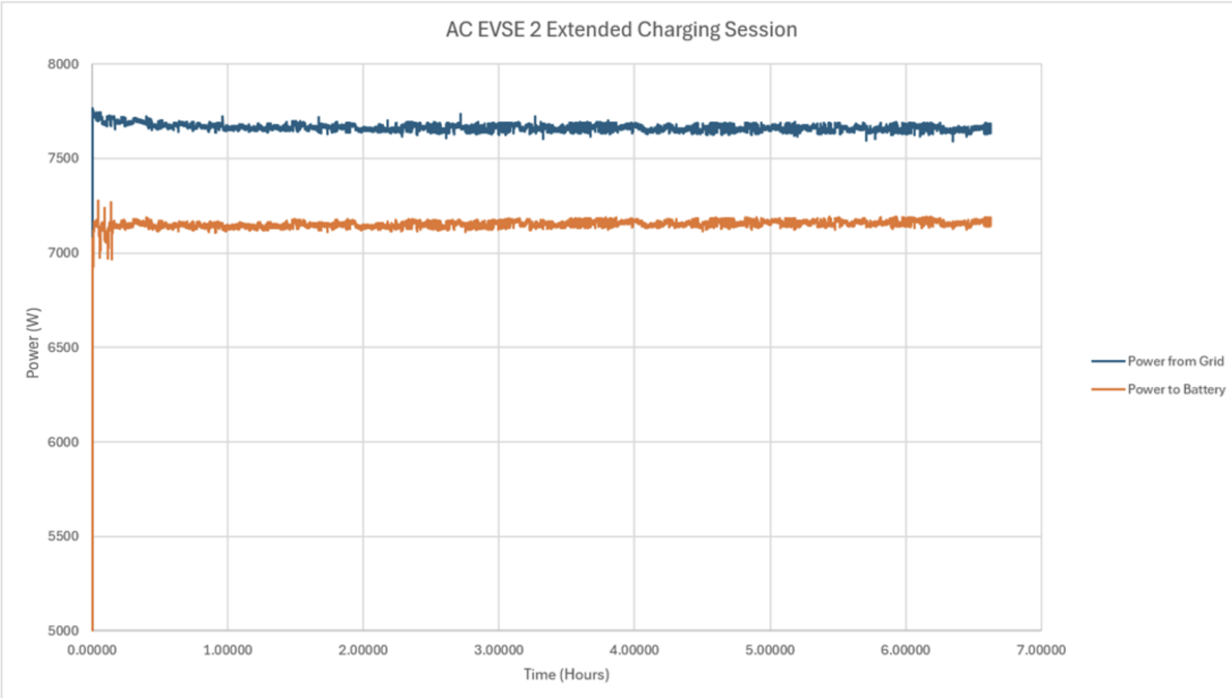

Figure 27: AC EVSE 2 power for extended charge session.

Source: CLTC

Figure 28 presents the measured efficiency profile for AC EVSE 2. Full-path efficiency averaged approximately 93.3 percent over the charging session and remained relatively constant across the evaluated SOC range. At the target SOC values, full-path efficiency increased slightly from 92.2 percent at 10 percent SOC to 93.1 percent at 25 percent SOC and 93.5 percent at 75 percent SOC. While a modest increase in efficiency was observed as charging progressed, overall variation remained small and the charging system demonstrated stable performance throughout the charging event.

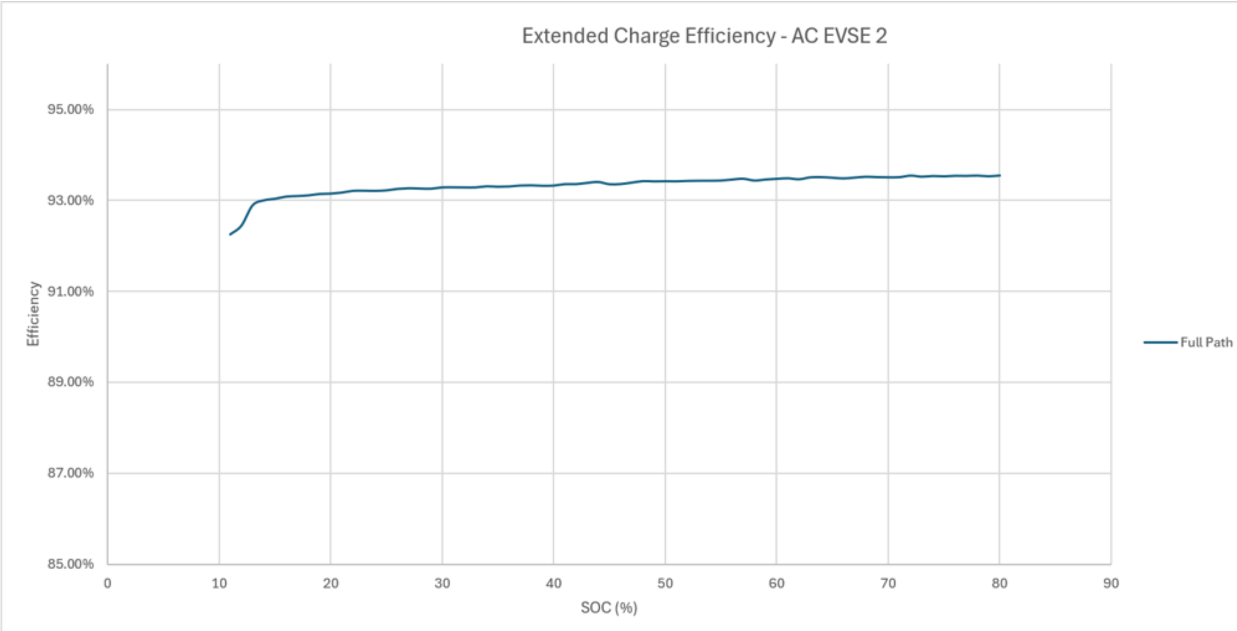

Figure 28: AC EVSE 2 efficiency for extended charge session.

Source: CLTC

Similar to AC EVSE 1, measured EVSE efficiency remained relatively constant throughout the charging session, indicating that charger losses contributed minimally to overall system efficiency variation.

DC EVSE 2

Unlike the AC charging evaluations, the vehicle high-voltage DC bus remained energized throughout the DC charging sessions. As a result, vehicle auxiliary systems including thermal management components, cooling pumps, and cooling fans operated intermittently during charging. These loads draw power directly from the vehicle DC bus and therefore contribute to the measured battery-side power values.

Consequently, the full-path efficiency metric presented in this section should not be interpreted solely as charger output delivered to the battery. Rather, the measurement reflects the combined effect of charger output, battery charging power, and concurrent vehicle auxiliary loads operating during the charging event. Periodic reductions observed in battery-side power measurements correspond to activation of these auxiliary systems and do not indicate charger instability or measurement error.

In addition to the standard instrumentation used throughout this project, Controller Area Network (CAN) data was successfully recorded during the DC charging evaluations; these measurements provided additional visibility into vehicle-side charging behavior, battery operating conditions, and auxiliary system activity. Similar CAN data was not available during the AC charging evaluations because the vehicle ceased updating CAN charging parameters after charging was initiated, preventing continuous data collection throughout the charging session.

DC EVSE 2 completed the charging event from approximately 10 percent to 80 percent SOC in 2.29 hours. Average EVSE output power during the charging session was approximately 21.2 kW.

Compared to the AC charging systems, DC EVSE 2 followed an initial ramp period, with charging power stabilizing near its operating setpoint and remaining relatively constant throughout the majority of the charging session after the first hour. It delivered substantially higher charging power and achieved the target SOC range in approximately one-third of the charging time.

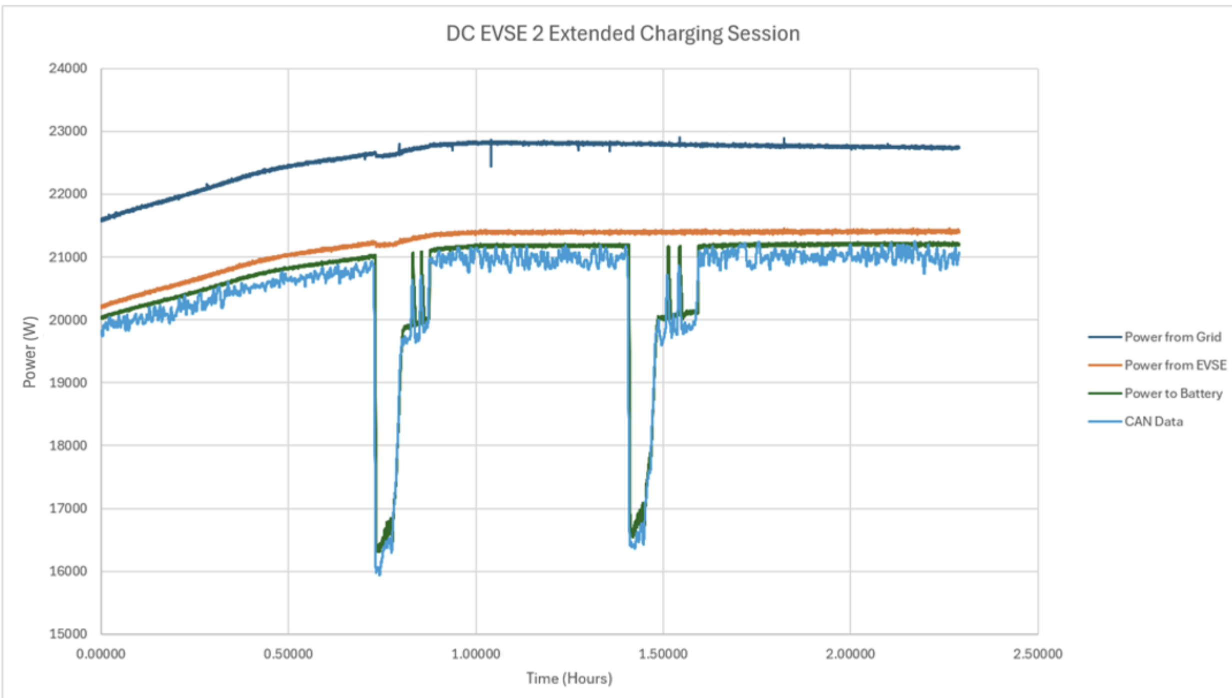

Figure 29: DC EVSE 2 power for extended charge session.

Source: CLTC

Figure 30 presents the measured efficiency profile for DC EVSE 2. Full-path efficiency averaged approximately 91.5 percent throughout the charging session, while EVSE efficiency averaged approximately 93.8 percent. At the target SOC values, EVSE efficiency increased slightly from 93.5 percent at 10 percent SOC to 93.7 percent at 25 percent SOC and 94.1 percent at 75 percent SOC. Corresponding full-path efficiencies were 92.7 percent, 92.7 percent, and 93.3 percent, respectively. The reductions visible in the full-path efficiency profile correspond to periods when vehicle thermal management systems were energized and drawing power from the active DC bus during charging. These events were confirmed through observation during testing and CAN data and do not indicate charger instability or measurement error.

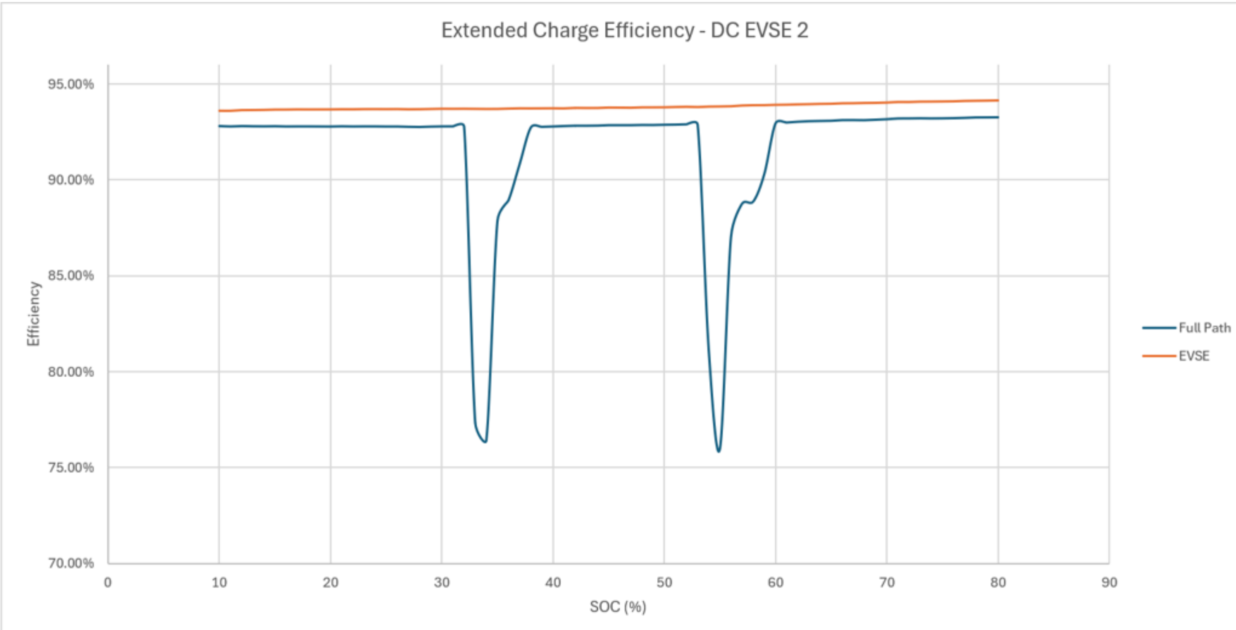

Figure 30: DC EVSE 2 efficiency for extended charge session.

Source: CLTC

DC EVSE 4

DC EVSE 4 completed the charging event from approximately 10 percent to 80 percent SOC in 2.14 hours. Average EVSE output power during the charging session was approximately 23.3 kW.

Charging behavior generally followed the expected DC fast-charging profile. During the initial portion of the charging event, the charger operated in a constant-current region, resulting in gradually increasing charging power as battery voltage increased during charging. As charging progressed, the system transitioned into a constant-voltage operating region—the charging current gradually decreased, producing the characteristic power taper observed at higher battery SOC levels. This charging behavior more closely reflects a conventional DC fast-charging profile than that observed for DC EVSE 2, which may have the constant voltage trigger set higher in its charging profile.

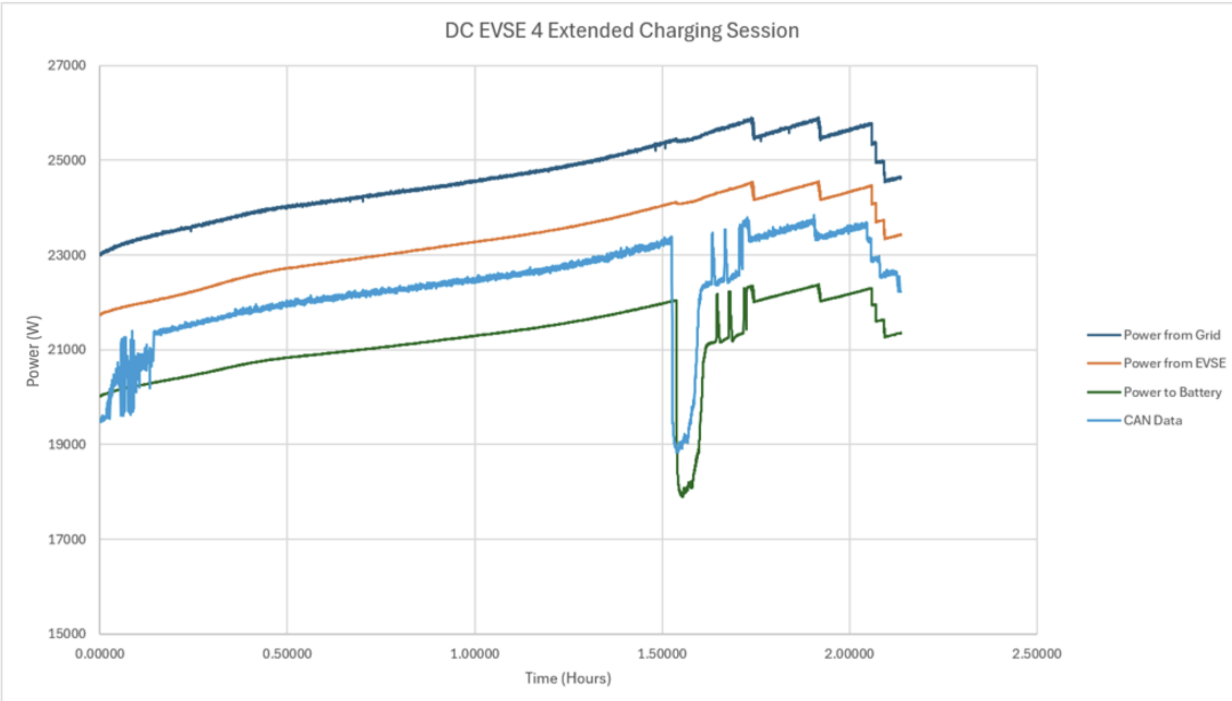

Figure 31: DC EVSE 4 power for extended charge session.

Source: CLTC

Figure 32 presents the measured efficiency profile for DC EVSE 4. Full-path efficiency averaged approximately 86 percent throughout the charging session, while EVSE efficiency averaged approximately 94.7 percent. At the target SOC values, EVSE efficiency remained highly consistent at 94.5 percent, 94.5 percent, and 94.9 percent for 10 percent, 25 percent, and 75 percent SOC, respectively. Corresponding full-path efficiencies were 87 percent, 86.8 percent, and 86.5 percent. As with DC EVSE 2, reductions in measured full-path efficiency were observed during periods of vehicle thermal management activity. These events were captured by both CAN and battery-side measurements; they are attributable to auxiliary vehicle loads operating during the charging session rather than changes in charger performance.

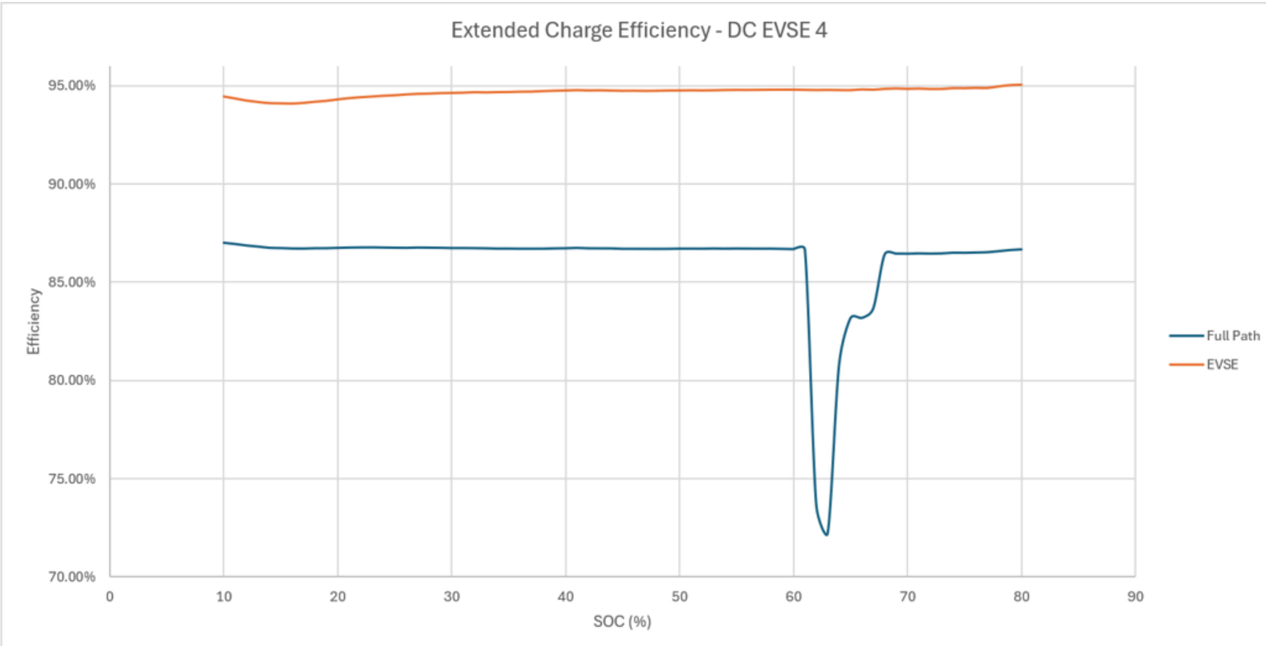

Figure 32: DC EVSE 4 efficiency for extended charge session.

Source: CLTC

Analysis: Phase 2

Figure 33 summarizes the average charging efficiencies measured during the Phase 2 evaluation. Due to differences in the measurement boundaries between the AC and DC charging configurations, the most representative efficiency metric for each charging architecture was used for comparison. For the AC systems, full-path efficiency was used with considerations for the low-voltage DC battery; as mentioned in Phase 1 testing, the DC charging pathway for AC input is separate from the one powering the high-voltage DC systems and is not influenced in the same way as the DC measurements. For the DC systems, EVSE efficiency was used because the energized vehicle DC bus supplied auxiliary vehicle loads throughout the charging session, introducing additional battery-side power consumption that is not attributable to charger performance.

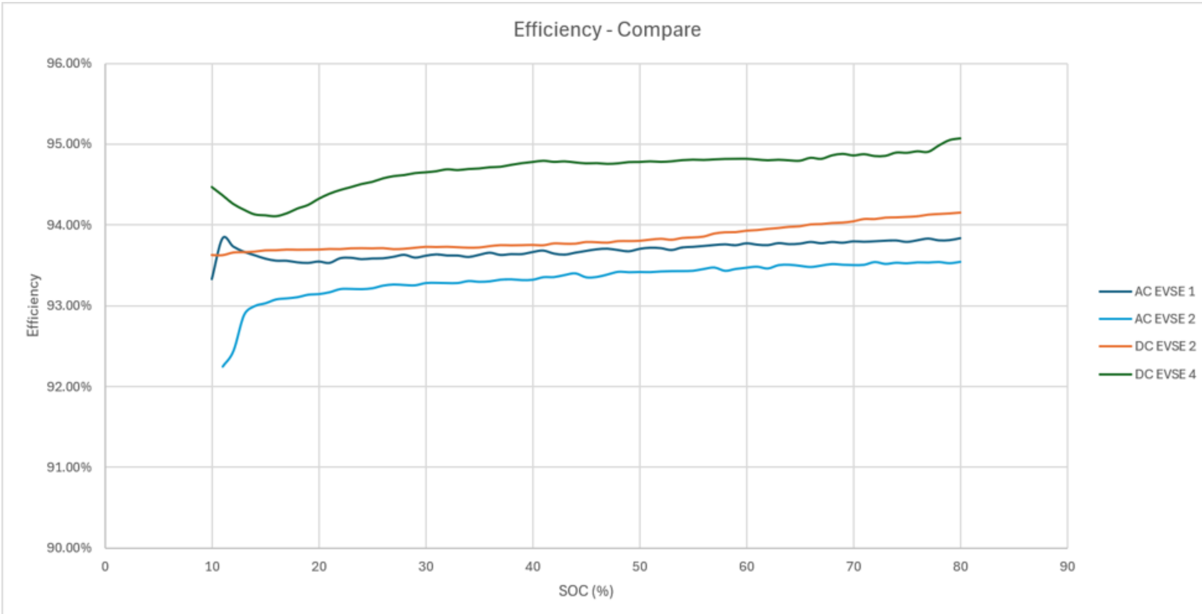

Figure 33: Phase 2 efficiency comparison.

Source: CLTC

Using these respective metrics, AC EVSE 1 and AC EVSE 2 achieved average efficiencies of 93.7 percent and 93.3 percent, respectively, while DC EVSE 4 and DC EVSE 2 achieved average EVSE efficiencies of 94.7 percent and 93.8 percent, respectively. The resulting efficiency range across all evaluated systems was relatively narrow, with less than two percentage points separating the highest and lowest performing systems. These results suggest that charging efficiency remained relatively consistent throughout the evaluated charging sessions, regardless of charging architecture.

Among the evaluated systems, DC EVSE 4 demonstrated the highest average charging efficiency, while AC EVSE 2 exhibited the lowest measured average efficiency. However, the magnitude of the observed differences was modest, indicating that all four systems maintained comparable energy transfer performance throughout the charging event.

Although the Phase 1 and Phase 2 datasets were generated using different test methodologies, the target SOC values provide a useful reference for examining how charging efficiency behaved under the two evaluation approaches. Table 27 summarizes the efficiencies measured near 10 percent, 25 percent, and 75 percent SOC during Phase 2, alongside the corresponding values observed during Phase 1.

Table 27: Target SOC comparison between Phase 1 (P1) and Phase 2 (P2) tests.

Target SOC	AC EVSE 1 – P1	AC EVSE 1 – P2	AC EVSE 2 – P1	AC EVSE 2 – P2	DC EVSE 2 – P1	DC EVSE 2 – P2	DC EVSE 4 – P1	DC EVSE 4 – P2
10%	91.60%	93.80%	91.40%	92.20%	95.40%	93.50%	95.60%	94.50%
25%	92.10%	93.50%	92.40%	93.10%	95.50%	93.70%	95.70%	94.50%
75%	92.50%	93.80%	92.50%	93.50%	95.70%	94.10%	96.10%	94.90%

Source: CLTC

Comparison of Phase 1 and Phase 2 results showed agreement between the two testing approaches, as illustrated in Figure 34. Across all evaluated systems, full-path charging efficiencies measured during the continuous charging evaluations remained within approximately one to two percentage points of the corresponding Phase 1 values, despite differences in test methodology and operating conditions. This close agreement indicates that charging efficiency remained relatively stable throughout the charging event and that the efficiency trends observed during Phase 1 are representative of real-world charging behavior.

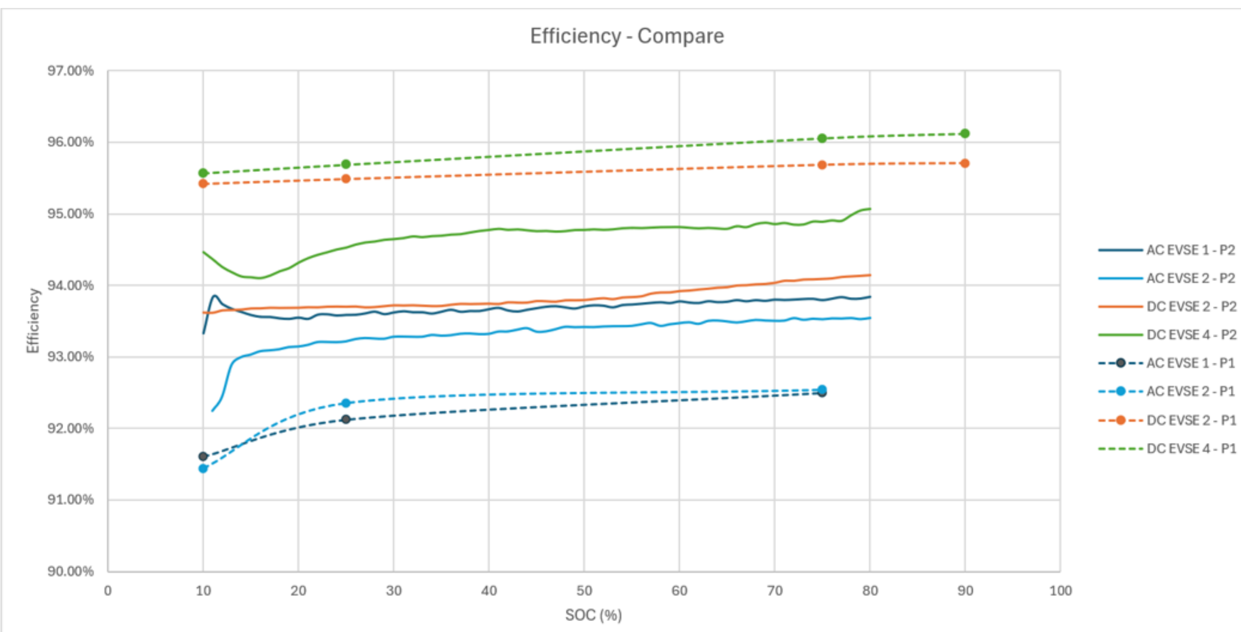

Figure 34: Efficiency trends for Phase 1 and Phase 2 testing.

Source: CLTC

Conclusion

This evaluation highlights the significant performance advantages of DC electric vehicle supply equipment over alternating current systems. While AC chargers consistently operated in the 91 percent to 93 percent efficiency range, DC chargers demonstrated efficiencies in the 95 percent to 97 percent range, particularly at higher default power levels. These results confirm that DC charging offers both higher energy conversion efficiency and greater power delivery capability, translating into meaningful system-level benefits, such as reduced utility bills and faster charge times.

It is worth noting that several of the tested units were ENERGY STAR–certified: two AC and one DC EVSE. However, certification status did not consistently correspond with higher measured efficiency. The DC certified unit outperformed all other chargers, while the certified AC units performed comparably to or below some non-certified models. This suggests that while certification provides a useful baseline for product quality, actual performance remains dependent on equipment design and operational characteristics beyond current labeling criteria.

At the statewide scale, transitioning from AC to DC charging could reduce annual energy consumption for California's light-duty zero-emission vehicle (ZEV) fleet by an estimated 173 GWh, avoiding more than 50,000 metric tons of CO_2e emissions each year. This reduction represents approximately 0.06 percent of California's total statewide electricity consumption in 2023 (281,140 GWh) (California Energy Commission, 2025), a modest yet measurable improvement at the system level. Although the absolute savings per vehicle may appear modest, the aggregate impacts are substantial given California's rapidly expanding ZEV adoption.

Economic analysis underscores that cost remains the primary barrier to widespread DC EVSE deployment. Current DC units command significantly higher upfront costs compared to AC alternatives, extending payback periods under today's rate structures. However, as the DC EVSE market matures, equipment costs are expected to decline, and targeted incentives could accelerate adoption. The long-term value proposition for DC EVSE is therefore closely tied to economies of scale, supportive policy frameworks, and continued technological innovation.

At the recommendation of SCE, Phase 2 testing expanded the evaluation to include continuous charging sessions using a subset of AC and DC EVSE systems. Unlike the discrete operating points evaluated during Phase 1, these tests assessed charging performance across a representative charging event from approximately 10 percent to 80 percent SOC. Results showed agreement with the Phase 1 findings, with charging efficiencies remaining within approximately one to two percentage points of the earlier measurements across all evaluated systems. These findings indicate that charging efficiency remained relatively stable throughout the charging event and that the efficiency trends observed during Phase 1 were representative of charging performance across a broader operating profile.

Overall, these findings suggest that DC charging infrastructure plays a critical role in advancing California's clean transportation goals. Strategic deployment of efficient DC EVSE, combined with thoughtful incentive programs and grid-integration strategies, can help the state maximize energy savings, lower greenhouse gas emissions, and provide more reliable charging solutions for drivers. To further support these outcomes, establishing performance-based efficiency benchmarks within EVSE codes and standards centered around combined efficiency metrics would help ensure that future supply equipment and electric vehicles meet consistent, measurable energy performance targets. Future work should continue to monitor technology trends, assess real-world performance, and explore pathways for reducing upfront costs, ensuring that California's charging network evolves to meet the demands of a fully electrified transportation system.

Future opportunities for technology transfer and continued research should build on the findings of this evaluation by expanding the dataset to include a wider range of charger products and vehicle platforms. Broader manufacturer participation and data sharing—particularly around measured energy throughput, mileage efficiency, and conversion efficiency—would enhance the robustness of future analyses and help establish greater transparency across the industry. Such collaboration would support the refinement of performance benchmarks and facilitate the integration of high-efficiency, grid-responsive charging technologies into California's evolving transportation network.

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