



EPRI

2023 TECHNICAL REPORT

Battery Performance Assessment of Vehicle-to-Grid Capable Electric Vehicles

Testing Methodology and Experimental Results

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Testing Methodology and Experimental Results

3002024770

Final Report, April 2023

EPRI Project Manager

S. Chhaya



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EPRI prepared this report.

Principal Investigator
S. Chhaya

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ABSTRACT

Electric vehicles (EVs) have experienced rapid growth in recent years, with a cumulative annualized growth rate of 45% and over 3.2 million EVs currently in the United States. This growth will continue at a 30% annualized rate over the next decade. EVs now come in several sizes and battery capacities, making them suitable for various applications.

One such application is vehicle-to-grid (V2G), which allows bidirectional charging and discharging of EV batteries to support grid services. This turns EVs into behind-the-meter energy storage systems. However, using EV batteries for mobility and V2G can result in incremental capacity degradation due to the additional charge-discharge cycles.

This project, supported by the U.S. Department of Energy Vehicle Technologies Office and the California Energy Commission, evaluated EV battery performance under mobility-only and mobility with V2G drive cycles. The project involved collaboration between an automotive original equipment manufacturer (OEM) (Stellantis), an automotive battery manufacturer (LG Chem), and research and testing organizations (National Renewable Energy Laboratory and its Energy Systems Integration Facility).

The accelerated testing generated data over four years of driving and charging/discharging. The research team hypothesized that incremental battery degradation due to V2G would be manageable as residential-level power cycling does not create significant heat within the battery, the primary cause of battery degradation.

Test results revealed that at a constant 30°C, EV-only battery degradation was about 1.5% per year. In contrast, daily use of 43% battery energy for V2G added 1.8% degradation per year. Over 10 years, this resulted in a 15% battery capacity fade for EV-only applications and a 33% capacity fade for joint mobility and V2G use. Despite this degradation, an additional 67% kWh from the battery were accessible for grid services applications.

Considering the 17.6 kWh nominal capacity of the tested plug-in hybrid electric vehicle (PHEV) battery (second-generation LG Chem, circa 2014), larger batteries of 60 kWh and above could offer significant opportunities for EVs to participate in energy markets without substantial battery capacity fade. Practical implementation would enable EV customers to manage this process effectively. The immediate use case of EVs to serve as backup power devices and limited grid services makes them available for customer-side resiliency applications.

Keywords

Vehicle-to-grid
EV battery testing
Capacity degradation
Vehicle-grid integration (VGI)
Battery test protocol

EXECUTIVE SUMMARY

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Primary Audience: Researchers at automotive, battery supplier, utility industries and universities; utility program managers interested in creating vehicle-to-everything (V2X) programs; grid flexibility-related program planners customer engagement staff; and executive leadership wishing to be informed about battery impact questions

Secondary Audience: General public, electric vehicle (EV) owners, EV manufacturers, and original equipment manufacturers (OEMs)

KEY RESEARCH QUESTIONS

How does the combined use of EV batteries for mobility and vehicle-to-grid (V2G) applications impact battery capacity degradation over time? What is a practical test cycle and test protocol to characterize the batteries? What are the cumulative impacts and implications of such capabilities in larger volumes?

RESEARCH OVERVIEW

A collaboration between an automotive OEM (Stellantis), an automotive battery manufacturer (LG Chem), and research and testing organizations (National Renewable Energy Laboratory and its Energy Systems Integration Facility) evaluated EV battery performance under mobility-only and mobility with V2G drive cycles. The research team conducted accelerated testing, generating over four years of driving and charging/discharging data. The team hypothesized that incremental battery degradation due to V2G would be manageable due to minimal heat generation at residential power cycling levels. By keeping batteries at a constant 30°C, they measured EV-only battery degradation and additional degradation from daily V2G use. The results helped assess the potential for larger batteries to participate in energy markets without significant capacity fade. The project was supported by the U.S. Department of Energy Vehicle Technologies Office and California Energy Commission.

KEY FINDINGS

- Data are provided on test cycles, methodology, and results for EV batteries in V2G applications.
- Four years of accelerated testing revealed EV-only battery degradation of 1.5% per year, with V2G increasing total degradation to 33% in 10 years. Despite this

degradation, an additional 67% kilowatt-hours (kWh) from the battery were accessible for grid services applications.

- Larger batteries of 60 kWh or greater offer the potential for EVs to participate in energy markets without significant battery capacity fade.
- The immediate use case of EVs to serve as a backup power device and limited grid services makes them available for customer-side resiliency applications.

WHY THIS MATTERS

This research offers valuable insights into the impact of V2G applications on EV battery degradation, which is crucial for applying EVs as value-providing grid resources. The findings help assess the potential of using EVs for mobility and grid services, offering a better understanding of battery capacity fading over time. Additionally, the results help identify opportunities for larger EV batteries to participate in energy markets without significant capacity loss, promoting more sustainable energy systems and supporting the transition to a low-carbon economy.

HOW TO APPLY RESULTS

V2G technology is hitting the mainstream and will be deployed at scale in the next 5–10 years as more and more OEMs bring these technologies to market and more customers opt for them as an alternative to having dedicated storage devices. Additionally, in California, the Net Energy Metering program (NEM3) must couple storage with local photovoltaics (PV) to maximize site benefits. Thus, any utility planning on creating backup power, V2G, or flexibility management programs should understand their impacts on EV batteries to result in a meaningful application of the technology at scale for utility programs.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- EPRI Program 18 base and several government projects provide excellent opportunities to learn more about V2G applications.

EPRI CONTACT: Sunil M. Chhaya, Senior Technical Executive, schhaya@epri.com

PROGRAM: Program 18, Electric Transportation

ACRONYMS

AH	Ampere Hour(s)
BMS	Battery Management System
CAN	Controller Area Network
CD	Cycle Discharge
EPA	U.S. Environmental Protection Agency
ESIF	Energy Systems Integration Facility (NREL)
EV	Electric Vehicle
gpm	gallons per minute
kWh	kilowatt-hour(s)
kW	kilowatt(s)
lpm	liters per minute
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturer
PEV	Plug-in Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
RPT	Reference Performance Test
SOC	State of Charge
V2G	Vehicle-to-Grid

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1 INTRODUCTION

Background: A Case for Vehicle-to-Grid (V2G)

With large-scale introduction of electric vehicles (EVs) across all transportation sectors – personal and fleet light-, medium-, and heavy-duty applications – the U.S. automobile industry is undergoing a once-in-a-century transformation away from fossil fuel dependence. With over 3.45 M¹ EVs in the United States by the end of February 2023, and cumulative average growth rate (CAGR) of about 35%, the technology is poised to supplant internal combustion engine (ICE) vehicles in all but the niche sectors within the next two decades, as shown in Figure 1.

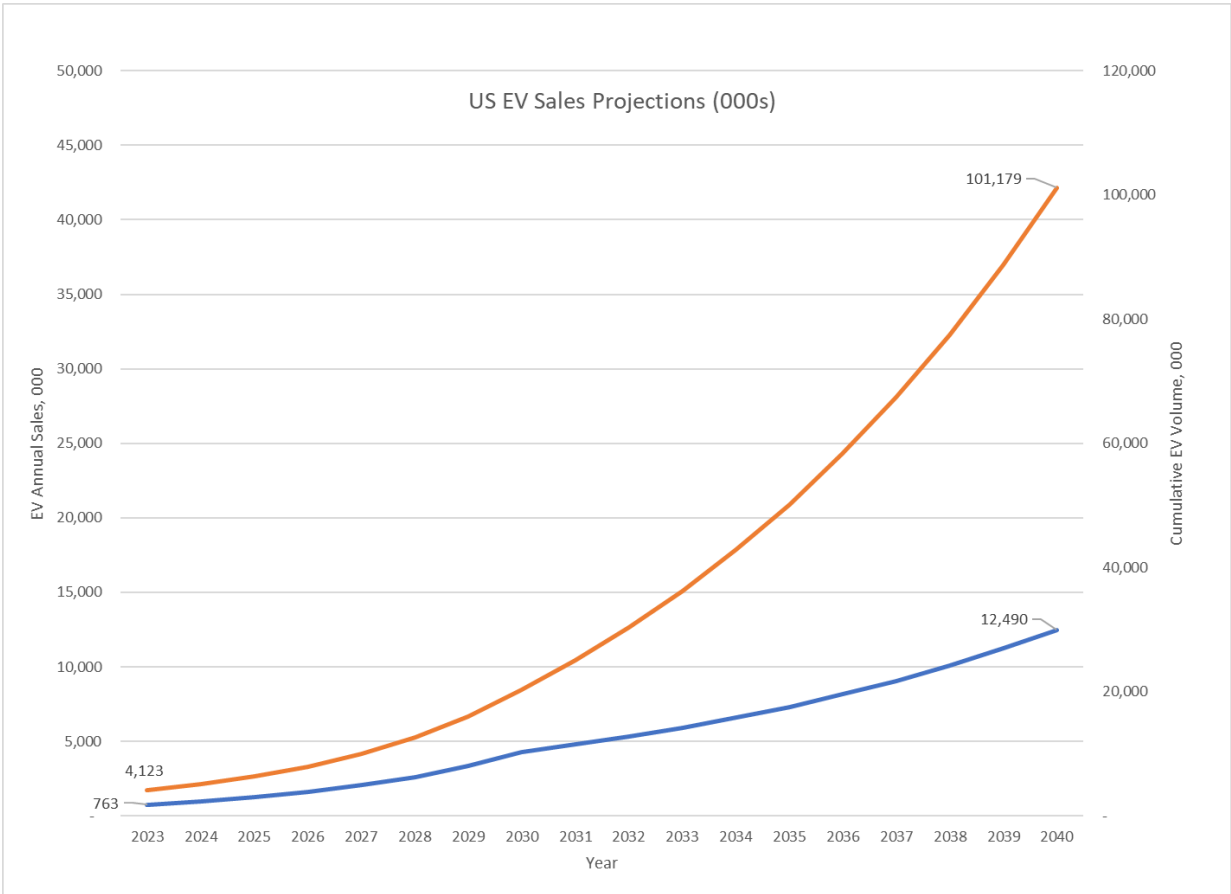


Figure 1. U.S. EV sales projections (Source: EPRI analysis)

¹ *Light Duty Electric Drive Vehicles Monthly Sales Updates*. Argonne National Laboratory, 2023. <https://www.anl.gov/esia/light-duty-electric-drive-vehicles-monthly-sales-updates#>

This growth in EV sales has the potential to accomplish the dual benefit of reducing reliance on imported petroleum while enabling large-scale – up to 30% – reduction of carbon emissions within the United States attributable to the transport sector.

As with any new technology with disruptive potential, EVs also have initial cost challenges to overcome. On average, EVs cost about \$61,500² before any incentives, but EV operating costs, consisting of recharge energy costs and other routine maintenance items, are significantly lower. For EVs to scale and become commonplace and a major part of the installed base, as projected in Figure 1, however, the net costs to own and operate them must be lowered even further. Vehicle-to-grid (V2G) technology can be a crucial enabler in monetizing EV benefits beyond the savings from fuel switching.

As the transport sector becomes electrified, the grid will need to adapt so that EV recharging infrastructure can be integrated systematically and operated to maximize capacity utilization of the transmission and distribution grid. This requires EV charging, and where possible, discharging from and to the grid or locally to respond to varying grid conditions. If EV charging and discharging (where the EV is equipped with a bidirectional charger) can be managed in such a manner, more kilowatt-hours (kWh) can be delivered over the same wires by shifting charging off-peak. Such charging avoids both costly distribution system upgrades through peak shaving (i.e., discharging into the grid) as well as expensive electricity at demand peaks. These functions, collectively called grid services, require modified EV charging (and discharging) capacity consistent with grid preferences. Some avoided costs (or cost savings) can then be distributed to customers willing to allow their EVs to be charged and discharged in concert with grid preferences. These incentives can encourage prospective EV owners to buy an EV as their next vehicle.

Any grid services – facility-level peak shaving, distribution-level, or system peak shaving (distribution congestion mitigation or resource adequacy), renewable balancing, and energy arbitrage – invariably require EV batteries to sustain bidirectional energy flow. This additional energy throughput (total energy due to charging and discharging) attributable to grid services also causes EV batteries to lose capacity. Careful attention, therefore, must be paid while designing and operating EV batteries for mobility and grid services to ensure that overall vehicle performance and battery life are unaffected for the life of the EV.

Rationale Behind EV Energy Storage System Characterization

Lithium ion batteries used in plug-in electric vehicles (PEVs) have improved substantially since the mid-2000s (for example, in terms of chemistry, manufacturing consistency, control systems, and lifetime), but the incremental degradation from bidirectional operation has not been clearly measured. Providing this information to automotive original equipment manufacturers

² Jack Ewing, “Electric Vehicles Could Match Gasoline Cars in Price this Year.” *The New York Times*, February 10, 2023. <https://www.nytimes.com/2023/02/10/business/electric-vehicles-price-cost.html>

(OEMs) and battery manufacturers can inform product development and build broader market confidence in bidirectional charging technologies. For example, knowledge of battery degradation could help clarify potential warranty considerations or potentially support more active approaches to monitoring and managing a PEV battery for both mobility and electric services throughout the vehicle's operating life.

The primary purpose of an EV is mobility, and EV batteries are designed today to meet operational and life requirements related to mobility. These are correlated with warranty requirements (10-year, 150,000 miles equivalent) as translated to battery cycle life under all operating conditions. The latest generation of lithium ion batteries was introduced first in the mid-2000s and has since undergone rapid evolution through multiple iterations of development, manufacturing, electrochemistry, and vehicle integration and control systems. Thus, both automotive and battery industries have become more open to exploring the simultaneous use of automotive batteries for mobility and grid services. The incremental degradation impact on automotive batteries, however, is not clearly defined. During EV operating life, indiscriminate application of EV batteries for both mobility and grid services applications could potentially curtail battery operating life or range through rapid battery capacity degradation. Unmanaged application of onboard batteries for grid services would also impact the manufacturer's battery warranty. To avoid this, battery and EV manufacturers can cooperate to understand EV battery intended applications for non-mobility use cases.

One way to accomplish this is by characterizing battery degradation for simultaneous mobility and grid services applications. Once battery impacts are known, battery and EV manufacturers can design and manage the onboard energy storage system for mobility and non-mobility applications. During EV operation, they can carefully monitor the system and apply operating constraints for non-mobility applications as the primary use for onboard batteries remains for mobility.

Outline of the Technical Update

The remainder of the document focuses on the

- Study approach for assessing incremental battery capacity degradation
- Test results obtained from the continuous testing
- Interpretation of test results
- Examination of how these results could be applied in a real-world scenario

2 STUDY APPROACH TO ASSESS INCREMENTAL BATTERY CAPACITY DEGRADATION

A systematic assessment of battery performance and capacity impacts due to simultaneous mobility and grid services applications requires the following:

- Representative energy storage characterization test cycle
- Realistic test setup that enables consistent testing and replicability of outcomes
- Continuous testing for sufficient duration to draw meaningful conclusions

These steps are described in detail below.

Onboard Energy Storage Performance and Capacity Characterization Test Cycle

When an automotive manufacturer specifies the energy storage system, the specification takes into consideration the following aspects:

- Expected operating envelope – as derived from vehicle operating conditions – in terms of total energy, charge and discharge powers, energy consumption at specific power levels, and operating state of charge (SOC)
- Operating conditions such as temperature, voltage, and power and energy efficiencies
- Battery cycle life in conjunction with the specification about end-of-automotive life performance

Energy storage specifications for mobility purposes are derived based on significant modeling and analyses assessing vehicle operating conditions as well as energy and power demand requirements under worst-case ambient temperature extremes. The goal is to ensure that collectively a robust system design is specified and vehicle expectations from the energy storage system are accurately represented, with allowances for manufacturing and operating software tolerances (for example, accuracy of SOC and state-of-health estimators).

Typical vehicle operating cycles³ are defined by the U.S. Environmental Protection Agency (EPA) for fuel economy/energy consumption certification – broadly described as Federal Test Procedure (FTP) simulating city and highway driving and Supplemental Federal Test Procedure simulating a high acceleration aggressive urban/suburban driving cycle (US06) and an extremely high heat and humidity cycle requiring air conditioning (SC03).

³ Vehicle and Fuel Emissions Testing: Dynamometer Drive Schedules. EPA. October 24, 2022. <https://www.epa.gov/vehicle-and-fuel-emissions-testing/dynamometer-drive-schedules>

These driving cycles assume mobility-only application of EV batteries. Therefore, the batteries specified as using these cycles under extreme operating conditions will have no additional energy throughput available to perform any type of grid services. *However, very few EVs operate under extreme operating conditions in terms of temperature, SOC, power levels, energy levels, and charge/discharge cycles during their entire life.* This means that most EV batteries – if the EVs are driven under average conditions, following average traffic patterns, under four-season ambient operation – will not have degraded to their specified end of life by the end of 10 years or 150,000 miles. Indeed, teams of researchers are now predicting that the batteries will last a million miles,⁴ meaning 150,000 miles of automotive driving may barely cause any battery capacity degradation.

Factors Affecting EV Battery Capacity Degradation

Factors affecting EV battery capacity degradation (defined as the loss of useful energy from the battery on an annual basis) include the following:

- **Calendar life** – A battery, even without any actual use, loses capacity just by sitting on the shelf for an extended period. Calendar life of an energy storage system could be 20 years or more.
- **Operating temperature** – When an EV is driven, the batteries are subjected to high power charge and discharge cycles during braking and acceleration events. These produce a tremendous amount of heat due to ohmic losses, which are proportional to the square of the battery current. A typical battery with 95% efficient charging or discharging, for an EV capable of producing 300 kW of acceleration power, generates upwards of 15 kW heat in the batteries for short bursts. If this heat is not removed from the cells to maintain a uniform operating temperature, the battery capacity degrades faster (any temperature outside of 15–35°C is considered extreme).
- **Charge and Discharge SOC Levels** – Charging the battery all the way to 100% or discharging it all the way down to 0% frequently results in accelerated degradation. All else being equal, the product of the SOC range and the cycle life is somewhat constant. The broader the SOC range (as indicated by the difference between maximum charging vs. minimum discharging SOC values), the lower the cycle life.
- **Environmental Factors:** Quality of the cooling medium and humidity can also affect battery life.

⁴ Jessie E. Harlow, et al., “A Wide Range of Testing Results on an Excellent Lithium-Ion Cell Chemistry to be used as Benchmarks for New Battery Technologies,” *Journal of the Electrochemical Society*. 166 (13) A3031-A3044. <https://iopscience.iop.org/article/10.1149/2.0981913jes>

Description of Battery Test Cycles for Mobility and V2G Performance Assessment

Table 1 summarizes the daily drive cycle simulated including total energy throughput and net energy consumed (accounting for energy recovered through regenerative braking) as well as the amount of energy remaining for grid services. Cycle discharge (CD) indicates the energy utilized while driving the EPA CD1 city and CD US06 test cycles used for vehicle fuel economy assessment.

Table 1. Mobility and V2G services related parameters

	Cycle	Time (hour)	Distance (miles)	Energy Throughput (kWh)	Net Energy (kWh)
Cycle discharge	CD1 City	0.3811	7.44	3.96	2.24
	CD US06	0.1667	8.01	5.27	2.81
Total		0.5478	15.45	9.22	5.05
Total usable energy from battery (kWh)				12.8	
Usable energy remaining after both drive cycles (kWh)				7.75	
Discharge power for grid services (kW)				7.6	
Discharge duration (hour)				1	

Sources: Stellantis and National Renewable Energy Laboratory (NREL)

Table 2 shows how both the baseline and test battery packs were cycled for a representative day. With a total cycle time of 6 hours, each battery pack could complete the test cycle four times per day.

Table 2. Baseline and test battery pack cycle durations

	Cycle Time (hours)	
	Test (Mobility+V2G)	Baseline (Mobility-Only)
Drive home from work	0.5	0.5
Home discharge at 7.6 kW	1	0
Charge to 100% SOC	2	1
Wait (contactor open)	1	3
Drive to work	0.5	0.5
Charge 50–100% at work	1	1
Total time per cycle	6	6

Pictorially, the same test cycles are shown in Figure 2.

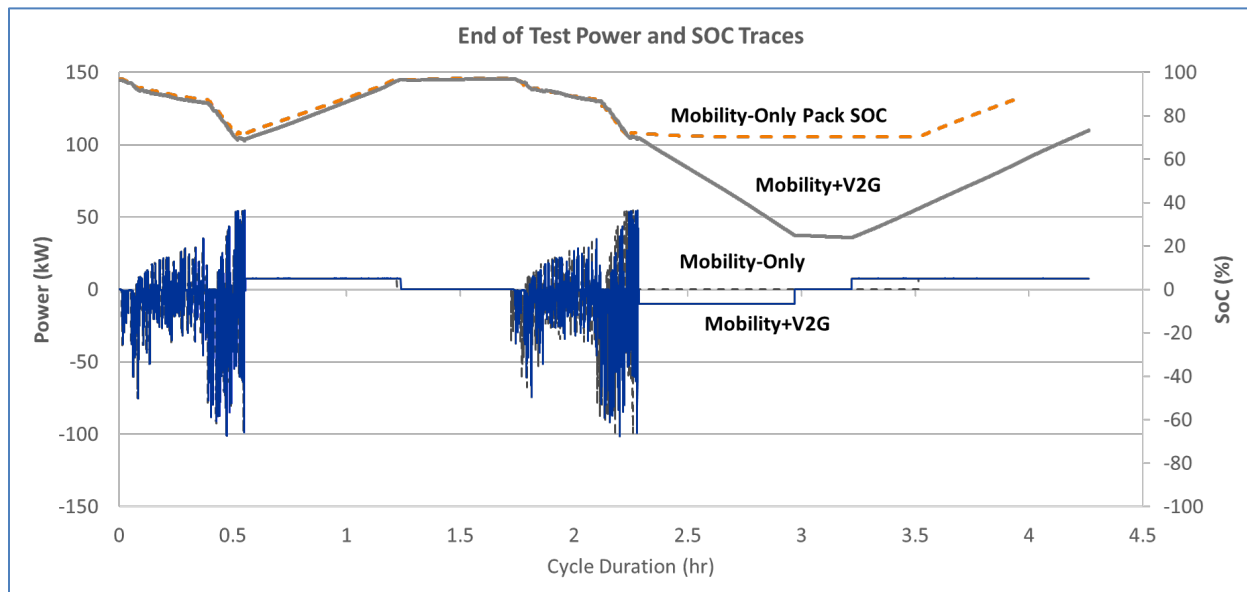


Figure 2. Pictorial view of the battery test cycle (measured data) showing mobility and V2G charge/discharge profiles with SOC

Assumed Vehicle Operational Profile Governing the Test Cycles

The assumptions behind this battery test driving cycle are as follows:

- EV owner will commute to work once per day, traveling about 30 miles round trip (U.S. average is about 25 miles), following an aggressive driving profile (represented by US06 drive cycle).
- EV will be recharged at work to full capacity and then have a dwell time for a few hours.
- EV owner will return home from work, following a similar aggressive driving pattern.
- EV will then be used for grid services type applications that require batteries to discharge into the home or the grid until the SOC reaches about 30%.
- After a dwell time of about an hour, the batteries are recharged overnight to full; the cycle restarts the next morning.

While it is not obvious from the Table 2 description, the graphical representation of the power against time during mobility in Figure 2 – the 0.5-hour intervals with power excursions in the +50 kW (charge) to -100 kW (discharge), implementing the CD1 city and CD US06 cycles, followed by very benign charge/discharge cycles at about 7.6 kW each – shows a stark difference in how they impact the batteries. EV batteries are designed to withstand power cycles resulting from EV driving (the large power swings), and the thermal system is designed to remove heat during these excessive power events. By comparison, the charge/discharge cycles

due to V2G are very benign (keeping in mind the square function of the current causing the heat dissipation). Thus, when the power level for charging or discharging drops from 50 kW to 7 kW ($1/7^{\text{th}}$), the heat generated drops by $1/49^{\text{th}}$ or 2% of the original heat dissipation, which is negligible. This was further verified through actual data. The expectation at the start was that if the charge/discharge power levels were kept within what is expected at the household load levels (3–5 kW on average), the EV battery should experience minimal degradation because the currents produced by this additional throughput have a benign effect on battery cell temperature.

3 ELECTRIC VEHICLE BATTERY CYCLE LIFE TEST SETUP FOR V2G APPLICATION

Test Setup for Simulating Real-World Operation with Replicability

The batteries employed for testing and cycle life characterization were obtained from LG Chem and were identical to the ones currently on board Chrysler Pacifica plug-in hybrid electric vehicle (PHEV). Key specifications for the batteries are as follows:

- Chemistry: Lithium ion, NMC (nickel-manganese-cobalt)
- Total kWh: 16
- Operating voltage: 360 V
- Operating temperature range: 15–35°C
- Manufacturer: LG Chem

Figure 3 shows the Chrysler Pacifica PHEV inside view as well as the battery pack as integrated into the vehicle.

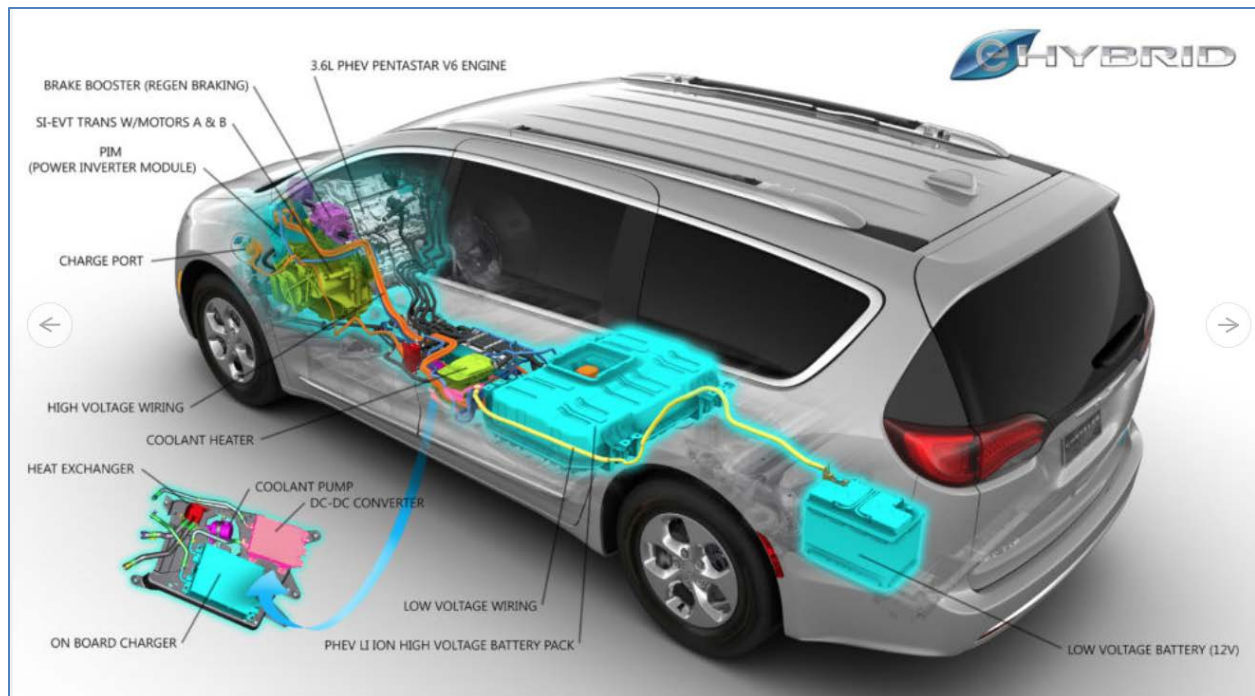


Figure 3. Inside view of 2018 Chrysler Pacifica PHEV showing the electrified powertrain components including the battery location (Source: Stellantis)

The light yellow lines indicate 12 V wiring, while the orange line indicates high-voltage wiring. The onboard charger is SAE J1772 Level 2 type. Given the low kilowatt-hours for this PHEV, DC fast charging was not considered a necessary option.

Figure 4 shows the battery pack with its external interfaces. Two of these battery packs were supplied by LG Chem at Stellantis' request to be used in testing for this project. The testing was performed at NREL's Energy Systems Integration Facility (ESIF), in Golden, Colorado. One pack was exercised as if driven daily as a PHEV for mobility only, while the test pack was exercised using the drive cycle described earlier to simulate mobility and V2G energy flow under the same operating conditions (voltage, temperature, and SOC range). This arrangement allowed change in cycle life to be solely attributed to the change in drive cycle.

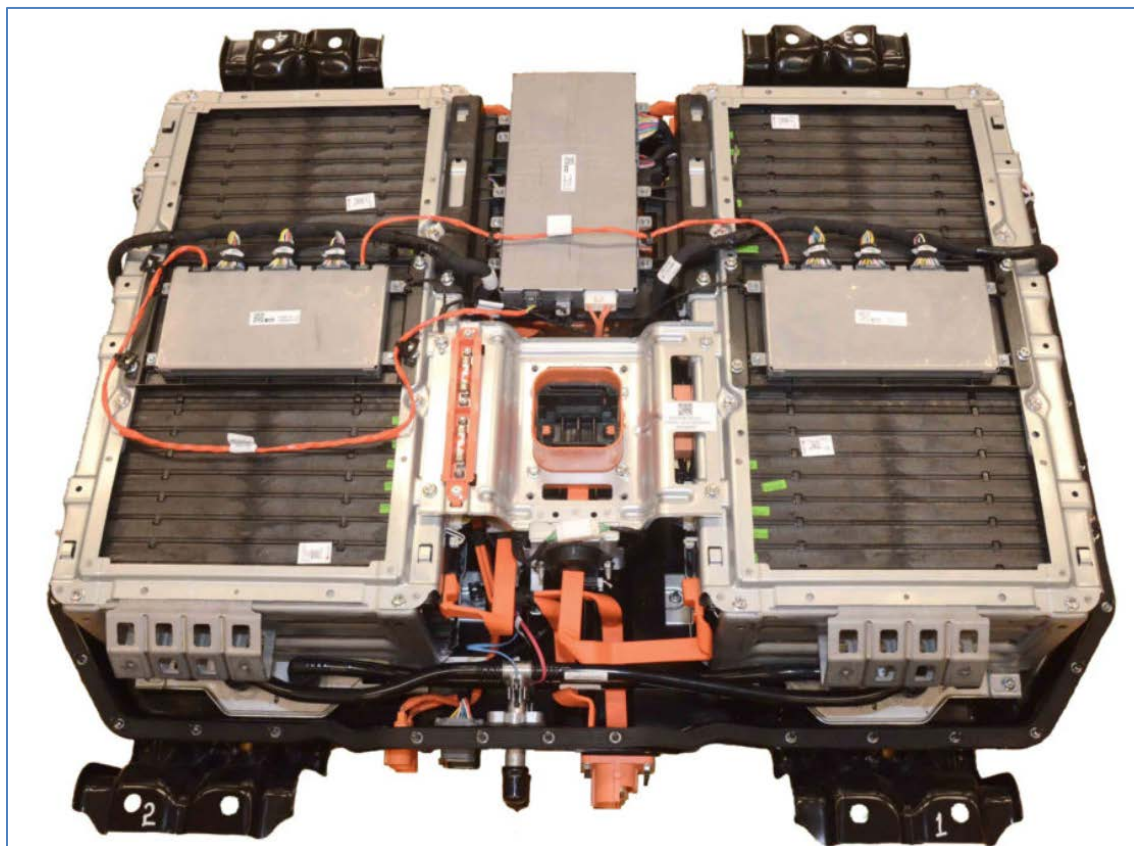


Figure 4. Model year 2018 Chrysler Pacifica PHEV battery pack mounted under the middle seat (Source: Stellantis)

Instrumentation and Test Apparatus Layout

The test setup required not only electrical connection of the power cycler to the charger but also integration of the cooling circuit and control electronics, such as the battery management system (BMS) with the laboratory instrumentation. This arrangement ensured that measured data from the instrumented packs, data available as digital signals from the BMS, and data from high-voltage contactors that needed to be managed externally so they could be opened and

closed during dwell periods replicated actual EV behavior during daily operation. This task of integrating the battery pack with lab instrumentation turned out to be non-trivial. The team persisted with it, because once the integration was achieved, the system could be cycled continuously without any manual intervention, significantly boosting productivity and accelerating data gathering. After several months of efforts by NREL engineers, assisted by the Chrysler team (during the pandemic with shelter-in-place orders, and restrictions on lab visits), this integration was achieved, and testing could begin. Figure 5 shows the in-lab setup in the form of a single-line diagram, indicating the battery packs, power, and control interface in addition to lab instrumentation.

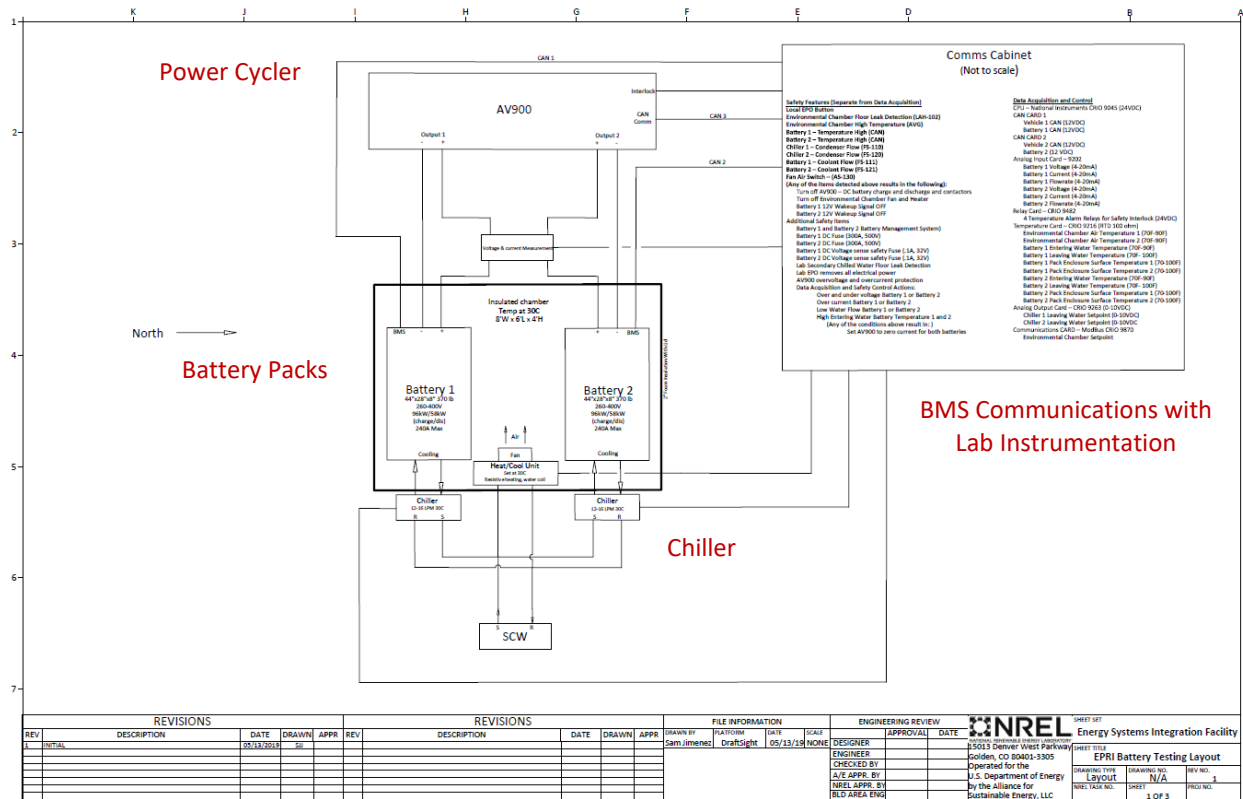


Figure 5. Single line diagram showing test setup at the NREL ESIF, Golden, CO (Courtesy: NREL)

The entire laboratory setup was computer-controlled, with the controller area network (CAN) channels across the equipment shown above facilitating data communications. The system was automated and had three independent monitoring systems (power, communications, and thermal) that could each shut down the experiment in keeping with the safety-critical nature of the battery technology being evaluated. Figure 6 shows the lab setup and communications overlay, including the layout of the actual test equipment in the ESIF battery test area.

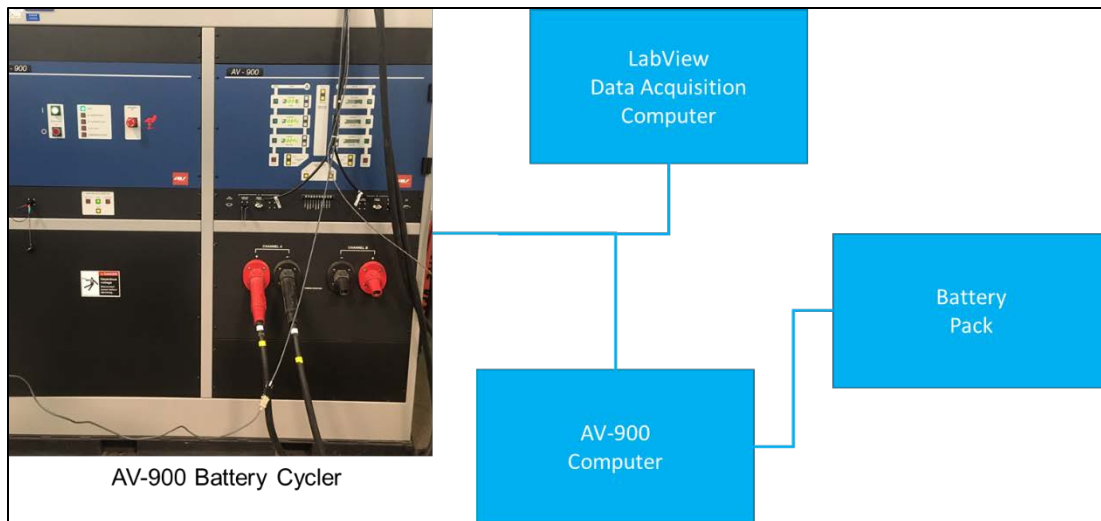


Figure 6. NREL ESIF in-lab control/communications setup for EV battery cycle life characterization (Courtesy: NREL)

Test Equipment Details

Figure 7 shows the two battery packs in a thermally insulated chamber with the communications interfaces that control the contactors and monitor their performance.

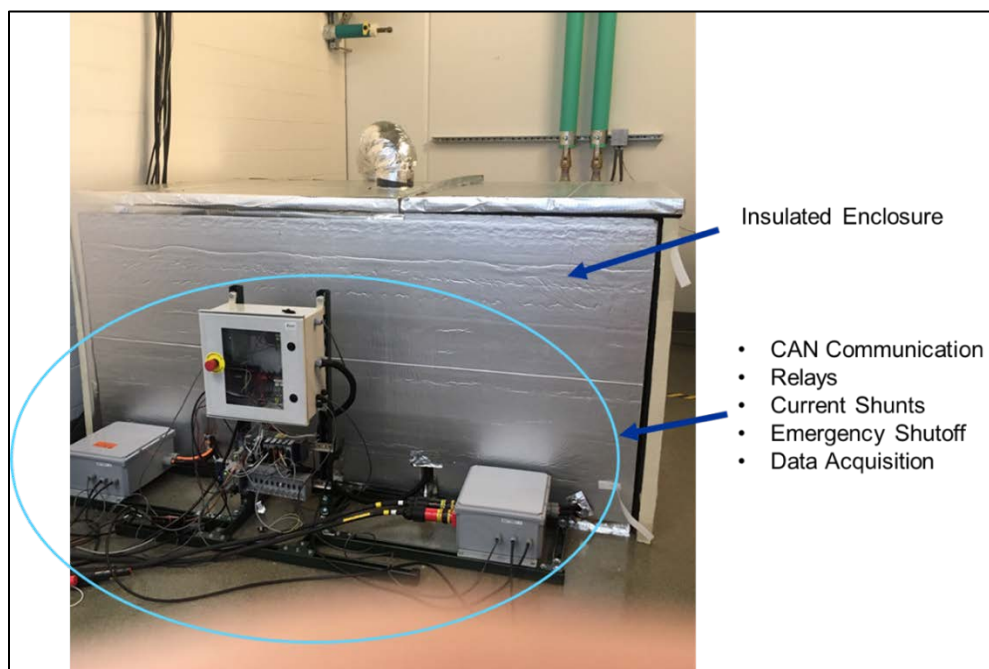


Figure 7. Battery packs in thermally insulated chamber with the communications interface

Figure 8 shows the chiller interface with the independent programmable chillers that control the operating temperature of each battery pack, allowing any ambient condition to be simulated using this setup. In this case, both were set at 30°C coolant inlet temperature with a flow rate of 12–16 lpm (3–4 gpm).

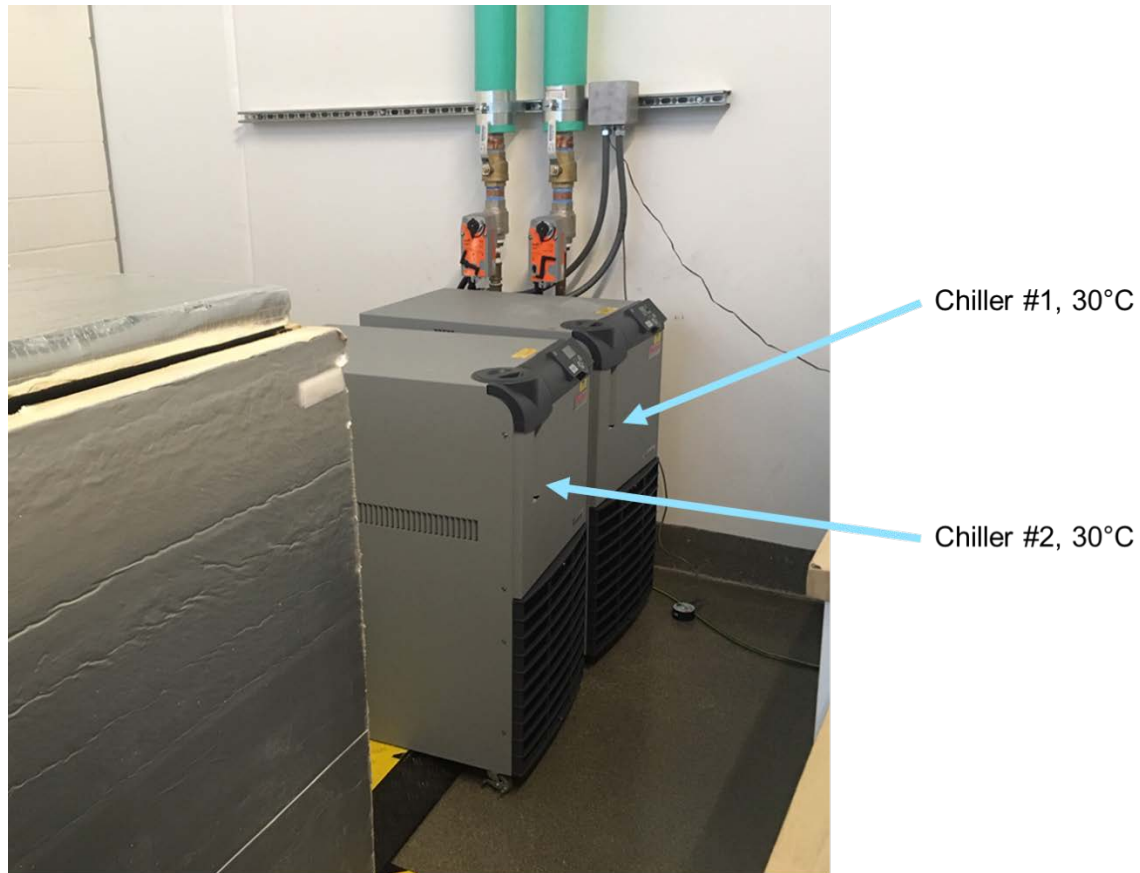


Figure 8. Cooling system setup with two independently controlled chillers for the battery packs under test

The air handling system – which is insulated and maintains a steady, programmable temperature for the battery packs – ensures that battery pack performance is measured under fixed operating conditions except for the load profile that the packs are exercised under.

All in all, this setup turned out to be an excellent way to manage the entire test regime. Once the system was set up for automatic, continuous testing, four test cycles could be exercised per day at six hours each, with appropriate resting period. This meant that in a month (30 days), 120 cycles could be conducted, and at 22 working days (commuting days) per month, about five months' worth of data could be acquired each month. Testing was conducted for 10 months, resulting in about 50 months' worth of driving data (i.e., 4.3 years). The following chapters discuss the testing profiles and results.

4 ELECTRIC VEHICLE ENERGY STORAGE V2G IMPACT TESTING RESULTS

Test Plan

The test plan included the following steps:

- Perform continuous testing, four cycles per day under identical operating conditions except for two different loading cycles for the two packs, generating four days' worth of data each day.
- At the end of each calendar month, perform the capacity test to monitor the battery kWh capacity and ampere hour (AH) capacity to track the change in capacity at regular intervals.
- Ensure the test remains continuously operational and remove any anomalies observed to maintain consistency in the results. For example, the team discovered in the first month some anomalies in the test cycle not being exercised appropriately, with only the charging part of the cycle implemented (no discharging), which meant the actual start of the testing phase was delayed by two months.

Typical battery performance and life testing protocols are standard⁵ within the automotive and battery industry, and this project used the same protocol, with the only change being the test cycle defined earlier.

The tests conducted are summarized below, and the results achieved are explained in a variety of terms.

Continuous Charge/Discharge Testing

Continuous charge/discharge testing refers to the 24-7 repeat of the battery test cycle as defined earlier. This is what the batteries are expected to be subjected to during their typical application for V2G in addition to mobility.

Reference Performance Test

A reference performance test (RPT) was conducted to perform periodic assessment of battery degradation during testing. In case of this project, this test was conducted once each month, on

⁵ *Battery Technology Life Verification Test Manual: Revision 1*. Idaho National Laboratory, U.S. Department of Energy Vehicle Technologies Program. INL-EXT-12-27920.

<https://avt.inl.gov/sites/default/files/pdf/battery/TechLifeVerificationTestManual.pdf>

a set date. The RPT generally consists of a few tests to ensure all parameters correlate well with each other. Several parameters are discussed below.

Capacity Test

The battery was discharged and recharged fully, and both the ampacity (coulombs, or charge, as designated by AH) as well as energy (Joules, as designated by kWh) were measured while charging and discharging between empty and full (0% and 100% SOC). This test showed how much energy the battery could absorb and discharge with high precision so any differences in capacity could be estimated.

Resistance Testing

One artifact of battery aging is not only its ability to deliver a specific amount of energy (defined, for example, by nameplate rating) but also its ability to deliver a specific amount of rated power. As the battery ages, its internal resistance increases, causing the terminal voltage to drop during loading. Given the voltage limit for the equipment connected to it and the voltage limitations, the current (or the power draw) of the battery declines with aging. The direct indication of this phenomenon is the measurement of internal resistance.

The following test results will now delve into how the batteries under test performed throughout the test period, which was equivalent to 4.3 years of use.

Test Results

The test results showed both the challenges encountered during the first month of testing followed by a very predictable performance from the batteries over time, indicating the validity of the test setup, test process, and test execution.

Test Process

Figure 9 describes the process employed to progress from test profile definition to published results and conclusions.

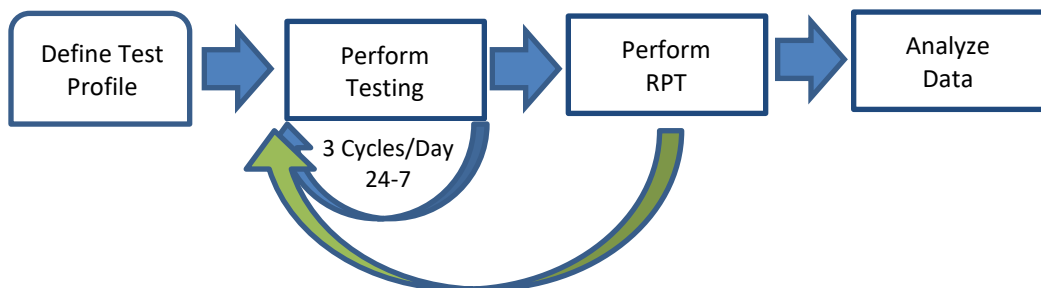


Figure 9. Energy storage V2G capacity impact testing process

Test Profile

The test profile was per the test plan agreed to by the battery and automotive EV technologists at Stellantis, LG Chem, and NREL. An intermediate test trace is shown in Figure 10.

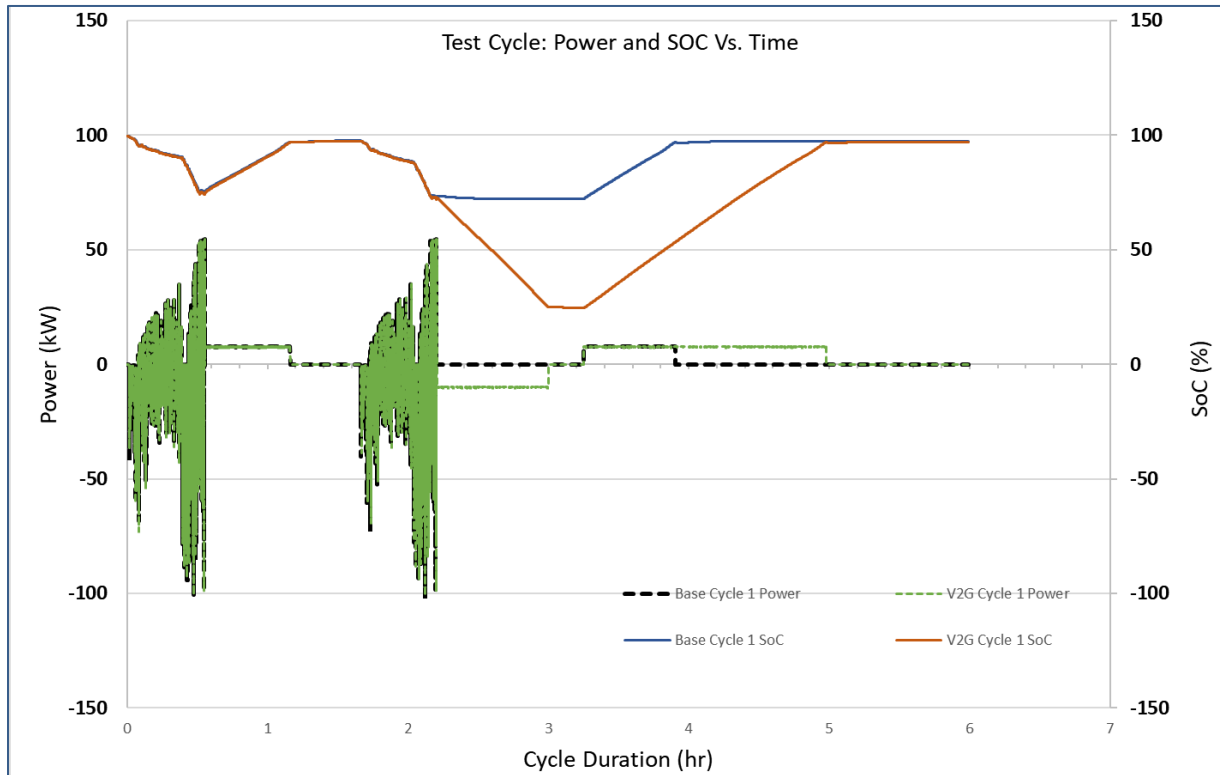


Figure 10. Measured test profile data, power, and SOC vs. time, one complete cycle with mobility-only and mobility+V2G packs

The test profile clearly shows two distinct 30-minute driving periods to and from work, charge power (marked as positive value) at work, and charge and discharge power cycles for mobility-only vs. mobility and V2G combined pack. SOC values were maintained appropriately so as not to violate the battery constraints (30–100%).

Accelerated battery testing (with approach and experimental setup described in Chapter 2) occurred at NREL from June 2020 through July 2021. The approximately 6-hour test cycle was run three times a day generating data equivalent to more than three years of daily operation. After discovering an error in the test profile in which the battery did not recharge with the energy recovered from braking while driving, the test profile was corrected in August 2020 and run continuously. Every month, RPT data were collected for the mobility only (baseline) and mobility plus grid services (test) batteries.

When comparing the test cycle shown earlier for the baseline and test packs, the driving and workplace charging sections of the profiles were identical for both packs (approximately hour 0 to 2.3). At home (approximately hour 2.3 to 3.3), the test battery began discharging

(representing V2G operation) at approximately 7.6 kW for approximately 1 hour. Over this time, the SOC of the test battery declined from 73% to 25% (a change of nearly 50%), while the SOC of the baseline battery remained stable at 73%. After discharging, it took longer for the test battery to fully recharge (approximately hours 3.2 to 5) at a steady rate of 7.6 kW (a 75% increase in SOC over 1.8 hours, or 13.68 kWh). At this point, both packs were fully charged and ready to be cycled again after a minimum period of 1 hour of stand time. The magnitude of power and current fluctuations for driving are significantly larger than for bidirectional operation, reflecting the relatively low power requirements of building electric loads compared to driving.

The modeled test cycle used about 8 kWh (50% for driving to and from work) of battery capacity daily for mobility services, which was approximately 36 miles total. The test battery discharged an additional 8 kWh daily, which represented nearly 50% of the total nameplate capacity (17.6 kWh) or 66% of the usable 12 kWh. While aggressive for daily use, this discharge profile was developed intentionally to accelerate the degradation and enable measurable differences between the baseline and test batteries.

Reference Performance Test Traces

RPT traces include the following information:

- Complete recharge and discharge energy and charge in terms of kWh and AH in and out of the battery
- SOC values
- Voltage and current values at cell and pack levels
- Coolant inlet temperature
- Internal resistance

Figure 11 shows these traces for the V2G pack at the beginning of the test process.

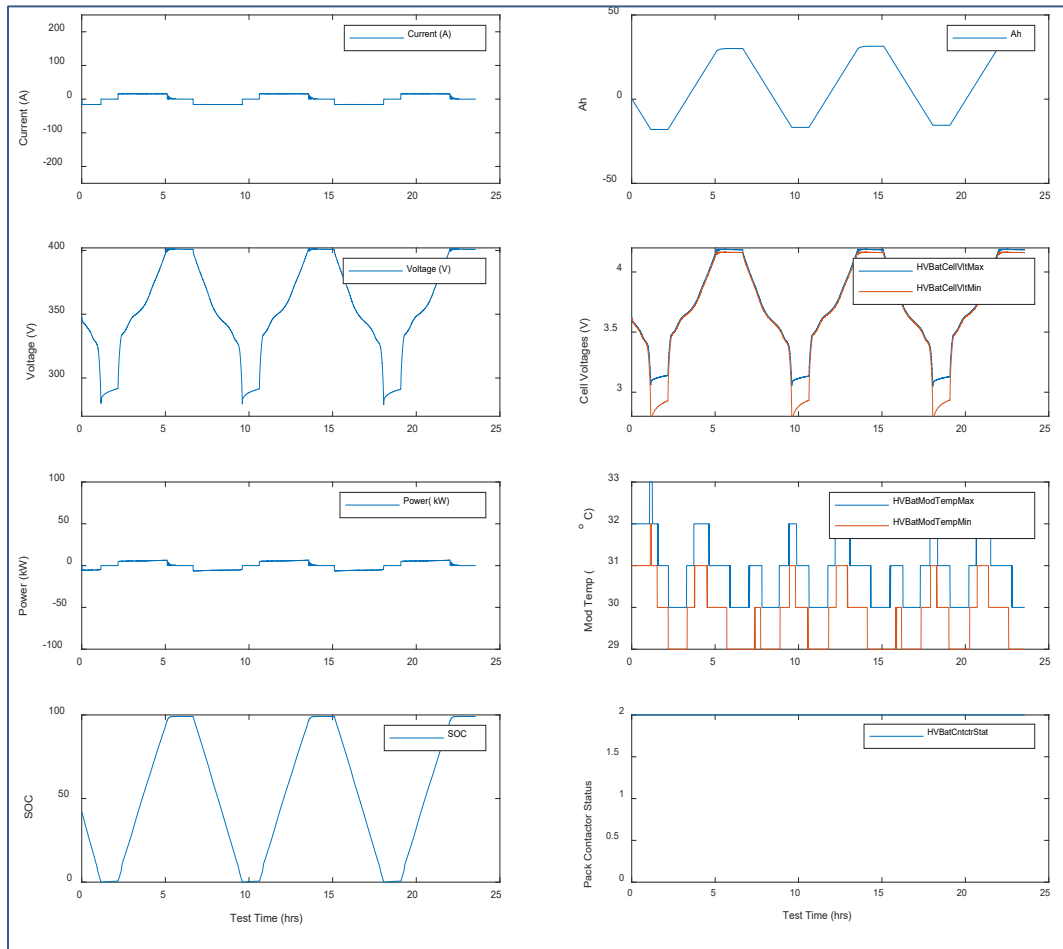


Figure 11. RPT traces, V2G pack, representative data

Note that the RPT was performed to measure kWh and AH capacity of the battery pack after it had been exercised continuously with the cycle depicted in Figure 10. Therefore, the RPT trace for the V2G pack and the baseline pack would look very similar, as seen in Figure 12.

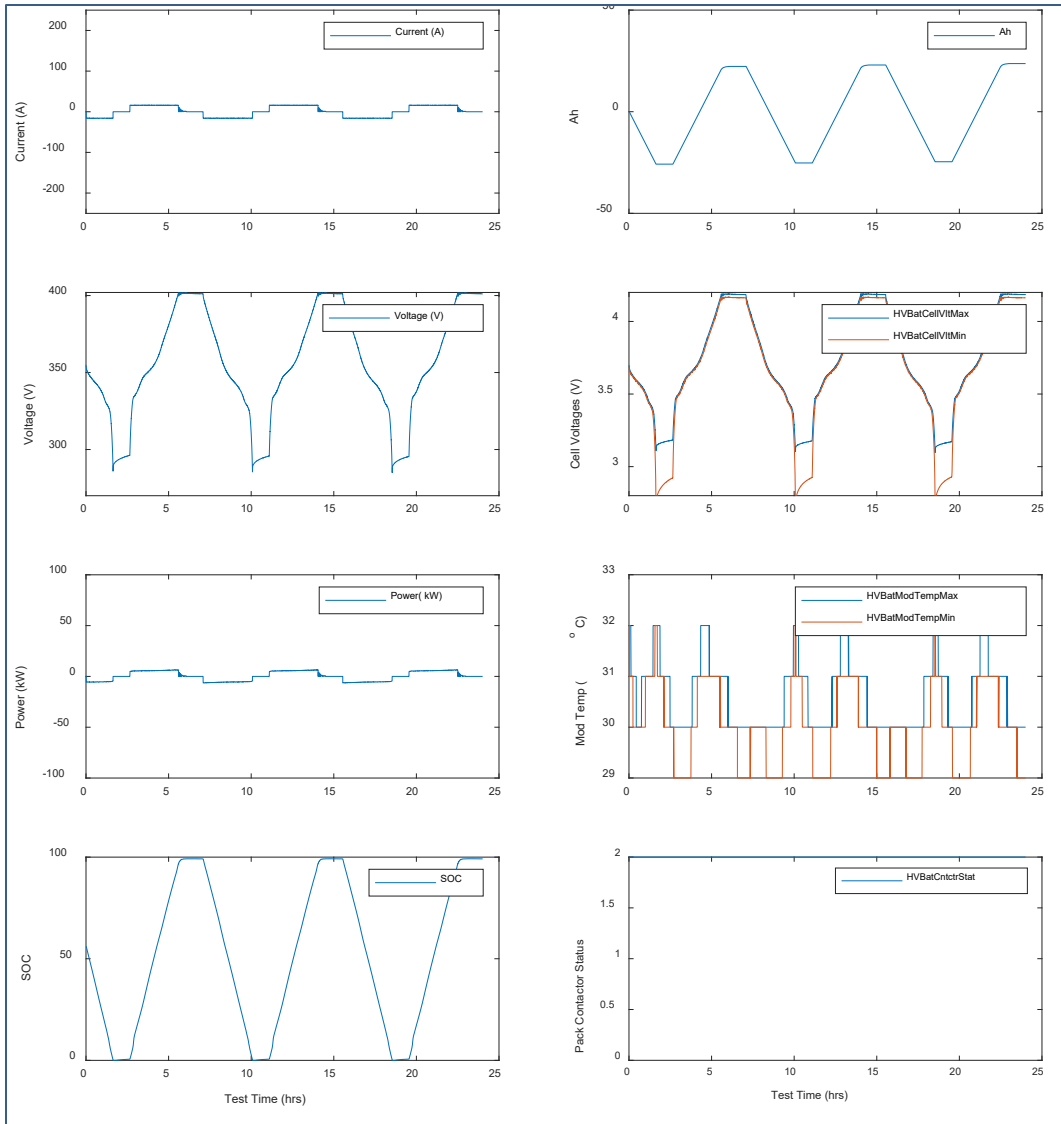


Figure 12. RPT traces for baseline (mobility-only) pack

Internal Resistance Test Data

Internal resistance change is a physical phenomenon where the electrode resistance physically increases with battery degradation. The extent of this increase can be interpreted as the extent of degradation that the battery is undergoing. The increase in internal resistance manifests itself in several ways. Since the electrical systems connected to the batteries are limited by their maximum and minimum voltage limits, increase in internal resistance would mean that to maintain the same terminal voltage levels, the charge current must be reduced, thereby imposing a limit on the charge (or regenerative braking) power. The discharge current also must be reduced proportionately, meaning the acceleration power must also reduce. Thus, an increase in internal resistance poses limits on battery charge and discharge power capabilities. Figure 13 shows RPT internal resistance traces for mobility-only and mobility+V2G packs, which

indicate a consistent 20% increase in the mobility+V2G pack as compared to the mobility-only battery pack. (Note: The Y-axis values are 0.08–0.22 ohms, with 0.02 ohms between two markers.)

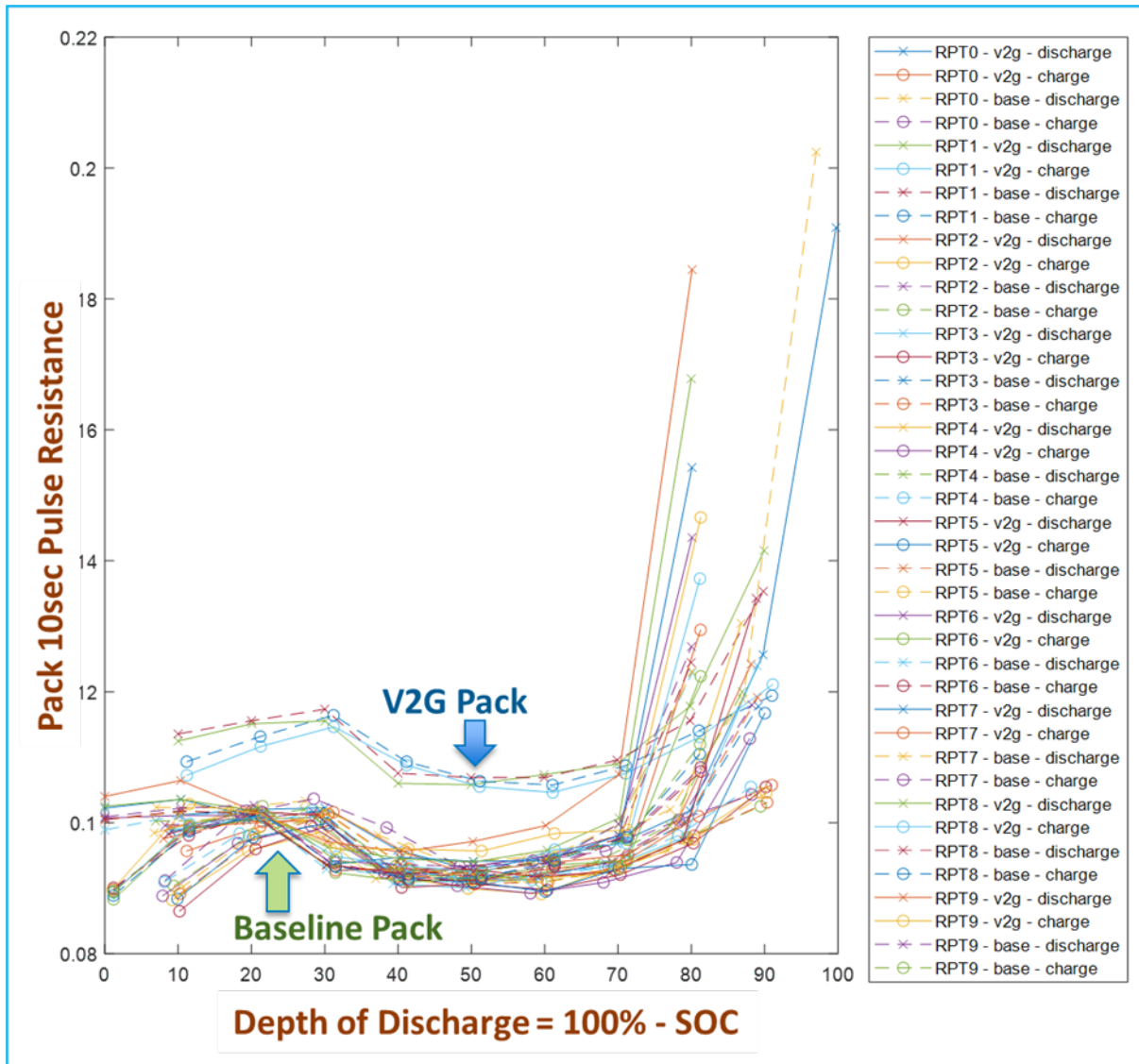


Figure 13. RPT internal resistance traces for baseline (mobility-only) and test (mobility+V2G) packs

RPT Cumulative Capacity Data

A running record of periodic RPTs was kept so a trend could be established with the increasing amount of cumulative kWh being processed by the energy storage systems from the baseline (mobility-only) and the test (mobility+V2G) packs. These trends are shown in Figure 14. The left-hand trace shows capacity degradation in terms of kWh for both the baseline and test packs, while the right half trace shows the same values in percentage terms.

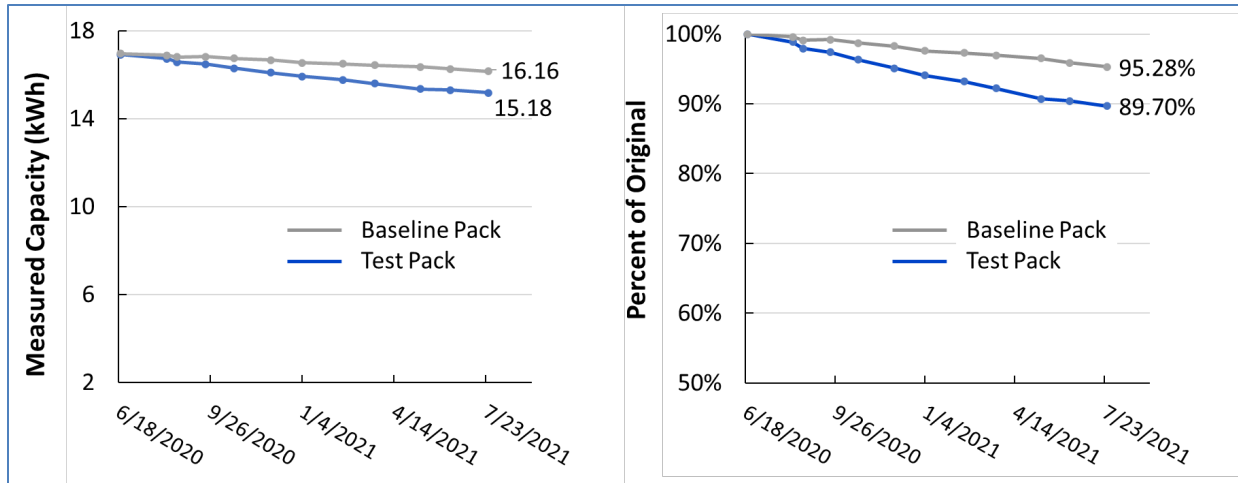


Figure 14. Capacity degradation data for baseline pack and test pack over 4.3 years equivalent of testing

The team measured capacity degradation in both the baseline and test packs at monthly intervals over the duration of testing. The left pane of Figure 14 shows the measured kWh capacity loss over time, while the right pane shows degradation as percent initial capacity. The slope of capacity loss was flatter during initial cycling with the error in the test profile (approximately June through August 2020). When the error was corrected, the slope of capacity loss became steeper for both packs (after August 2020), which makes sense as degradation increases with greater cumulative throughput. The loss in kWh capacity reflects both decreasing AH capacity as well as the effects of increasing internal resistance, which grows with cumulative throughput and calendar aging. Although not shown, comparison of the percent kWh and AH capacity loss suggests that increasing internal resistance has relatively limited impact on capacity loss (although it can result in power fade).

The measured energy (kWh) capacity degradation in the test pack is 10.3% (declining from 100% to 89.7%) compared to 5.7% for the baseline pack (declining from 100% to 95.3%). The system was tested at four cycles per day, for a period of 12 months, which is a total of 1460 cycles. Assuming a year has 260 working days, this implies about 5.6 years of battery cycling, resulting in an incremental capacity degradation of about 5.5% or approximately 1% capacity loss every year due to the aggressive discharging cycle. Extrapolating this data linearly, the baseline pack could lose 12–15% of its nameplate capacity at the end of 10 years. If the test pack continued discharging 8 kWh per day for performing local or grid services, the capacity fade would be an additional 10% over 10 years leaving about 75–78% of the original nameplate capacity available at the end of 10 years. This is generally within the terms of most warranty considerations and suggests that even smaller PHEV batteries have significant potential to provide both mobility and resiliency as well as grid services. After more than one year of accelerated testing, the batteries completed approximately 1460 full cycles (less than 200 cycles were completed with the erroneous test cycle before correcting). Cumulatively, the test pack discharged more than 6700 kWh for grid services such as backup power or rate arbitrage.

Table 3 shows the cumulative throughput obtained by the baseline and test packs, showing that significantly high (65%) additional battery kWh can be available for deployment toward grid services within this incremental capacity degradation. This is a significant finding, indicating that the batteries – when managed well within their acceptable temperature, SOC, voltage, and current ranges – are capable of providing significant additional value in terms of the additional kWh that can be deployed for grid services.

Table 3. Cumulative throughput comparison: mobility-only vs. mobility+V2G

Throughput	Units	Baseline: Mobility-Only	Test: Mobility+V2G	V2G in Excess of Mobility	V2G in Excess of Mobility (%)
Coulombic, Total	AH	60,300	99,785	39,485	70%
Coulombic, Charging Only	AH	30,200	49,989	19,789	71%
Coulombic, Discharging Only	AH	30,100	49,505	19,405	70%
Energy, Total	kWh	22,900	36,717	13,817	65%
Energy, Charging Only	kWh	11,700	18,698	6,998	66%
Energy, Discharging Only	kWh	11,300	18,019	6,719	64%

Compared to the baseline pack, the test pack had 65 or 70% greater throughput as measured by kWh or AH, respectively. On an annualized basis, the test pack provided an additional 11% (65% over 5.6 years equivalent) to 12.5% (70% over 5.6 years equivalent) throughput contributing to additional incremental degradation of 1% annually. Extrapolating these trends linearly suggests that at the end of 10 years, the test pack providing both mobility and electric services would contribute 112–125% of the cumulative throughput of the baseline pack providing only mobility while experiencing 10% additional loss of battery capacity.

Data Interpretation and How to Use This Information

Accelerated testing quantified the increased degradation experienced by the test pack relative to the baseline pack, which was expected given that degradation is a function of cumulative throughput. The relatively aggressive discharge cycle of approximately 8 kWh every day for local and grid services could provide enough energy to power about 46% of the average California home’s daily energy use. With a less aggressive discharge cycle (that is, less daily energy use as a fraction of total battery capacity), measured degradation would likely be even smaller. The project team developed the test profiles based on reasonable assumptions that would lead to quantifiable degradation; however, no standard test cycles or procedures currently exist for evaluating bidirectional charging impacts on PEV batteries. Automotive manufacturers likely have the driving and battery charging data that could inform holistic management of cumulative energy throughput for both mobility and electricity services over the life a vehicle. Recent OEM announcements to pursue bidirectional charging for backup

power applications suggest that they have sufficient confidence in the longevity and health of vehicle batteries.

Additionally, testing was done with PHEV batteries that are relatively small (generally less than 20 kWh) compared to all electric models (generally 60 kWh or greater). The 8 kWh discharged daily amounted to about approximately 50% change in SOC. Given the inverse relationship between cycle life and depth of discharge, it is reasonable to expect that PEVs with a larger battery would experience less degradation if discharging the same amount of energy. Alternatively, the larger battery capacity could be used to provide additional electric services – for example, a mid-size PEV using 40% of a 60 kWh capacity battery could discharge approximately 24 kWh daily. Furthermore, PEV batteries have continued to improve in cycle life and durability compared to the earlier generation batteries tested in this project.

In real-world use, battery degradation and energy management strategies are significantly more complex than reflected in the accelerated testing conditions. No two PEVs are driven and charged the same, and there is wide variability in operating conditions such as ambient and battery operating temperature. While driving is generally more burdensome on PEV batteries than charging or discharging for residential or grid energy services, there are many charging behaviors that can impact battery degradation beyond cumulative throughput. For example, frequently charging at high power levels or leaving PEV batteries at high SOC for long periods of time (such as fully charged and plugged in when out of town) can also accelerate degradation.

An emerging strategy is to pursue a holistic battery management strategy that continually monitors, predicts, and optimizes battery health based on factors such as age, past usage, and anticipated mobility needs. Such active battery management strategies could include discharging the PEV battery for electric services when there is limited impact on – or potentially even benefits to – battery health or when the value of the electric service exceeds that of lost capacity. This would require greater and more frequent communication between electricity systems, PEVs, and smart bidirectional chargers based on driver willingness to participate and schedule flexibility. The data collected through this project can help battery and automotive manufacturers understand how discharging for electricity services impacts PEV battery degradation. The project can also inform development of new battery management approaches, for example developing control setpoints based on cumulative kWh throughput and predicted state of health, among other factors.

5 CONCLUSIONS AND SCOPE OF FUTURE WORK

Summary of Testing Performed

This project was conducted as an adjunct to a V2G technology development project, which designed, developed, and tested a V2G capable integrated distributed energy resources (DER) system. The work described in this project answered a key question around the battery performance impacts due to the application of EV batteries in V2G-related use cases.

To study this impact, EPRI convened a team of experts spanning the automotive manufacturer (Stellantis) and battery testing experts (LG Chem and NREL), developing a test plan that would represent real-world driving conditions as experienced by the battery. The team also defined a test setup that would be capable of implementing this test protocol using the battery industry standard methodologies so the results could be interpreted similar to how other battery capacity testing is routinely performed.

Stellantis and LG Chem provided two identical (similarly aged, and otherwise the same) battery packs that are currently in the Chrysler Pacifica PHEVs. These packs were tested at NREL's ESIF in Golden, CO, under identical operating conditions except for the test cycles, so that the results would show a direct impact only of the varying loading patterns attributable to the mobility-only and mobility+V2G cycles.

Opportunities for Applying Results

The end results showed a pattern consistent with the original hypothesis, which was that the mobility+V2G test pack would experience a higher capacity fade. What was surprising was the small extent to which this capacity degradation was experienced for the large amount of incremental throughput that could be obtained. The reason behind this is the relatively benign power and current levels that are relevant to residential grid services. Clearly, power and current levels are significant drivers of capacity degradation.

This research provides the opportunity for the EV manufacturers to create applications that require infrequent use of battery energy under controlled circumstances. Examples of these are providing backup power needed only during infrequent outages or slow charging and discharging following solar generation and residential energy profiles indicating vehicle-to-home applications. Indeed, this is where much automotive industry attention is focused.

In case of a utility company interested in offering backup power or grid flexibility type programs, the results indicate that if the energy and power demand are within reason (up to 10 kW, 20–40 kWh) and are slow moving – as signaled through tariff changes and real-time pricing signaling – EV batteries are more than capable of providing these services on a regular basis. This opens significant possibilities to create programs that benefit the EV owner as well as the grid, without the need for costly backup power generators or stationary storage devices.

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Electric Transportation

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EPRI

3420 Hillview Avenue, Palo Alto, California 94304-1338 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com