Energy Research and Development Division

FINAL PROJECT REPORT

Vehicle-to-Grid Testing and Demonstration

California Energy Commission
Edmund G. Brown Jr., Governor

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PREFACE

The California Energy Commission entered into an agreement through the Alternative Renewable Fuel Vehicle Technology (ARFVT) Program with California Institute of Technology to accelerate developing liquid fuels directly from sunlight through molecular catalysts and membranes. Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007), created the ARFVT Program. The statute, amended by AB 109 (Núñez) Chapter 313, Statutes of 2008), authorizes the California Energy Commission to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. The Energy Commission provides financial support for projects that:

- Develop and improve alternative and renewable low-carbon fuels.
- Enhance alternative and renewable fuels for existing and developing engine technologies.
- Produce alternative and renewable low-carbon fuels in California.
- Decrease, on a full-fuel-cycle basis, the overall impact and carbon footprint of alternative and renewable fuels and increase sustainability.
- Expand fuel infrastructure, fueling stations, and equipment.
- Improve light-, medium-, and heavy-duty vehicle technologies.
- Retrofit medium- and heavy-duty on-road and non-road vehicle fleets.
- Expand infrastructure connected with existing fleets, public transit, and transportation corridors.
- Establish workforce training programs, conduct public education and promotion, and create technology centers.

To be eligible for funding this project was consistent with the Energy Commission's ARFVT Investment Plan, updated annually.

ABSTRACT

Widespread adoption of plug-in electric vehicles is critical to achieving California's low-carbon transportation goals; however, high vehicle cost remains one of the primary barriers to increased market penetration. Preliminary analyses of the ability for plug-in electric vehicles to provide grid resources through development of vehicle-to-grid technologies indicate that the associated economic benefits could be positive under the right conditions, and potentially significant enough to offset the higher upfront cost of the vehicles. Additionally, strategic integration of plug-in electric vehicles can provide grid stabilization opportunities through aggregated storage and ancillary services strategies.

The U. S. Department of Defense conducted a vehicle-to-grid demonstration at Los Angeles Air Force Base and explored revenue generating capability of such a fleet by participating in the frequency regulation market for California Independent System Operator's ancillary services. Repurposing electric vehicles battery packs after they have lost their effectiveness for vehicle primary use has the potential to decrease the total lifetime cost of ownership of plug-in electric vehicles batteries. These battery packs are typically removed from service with significant capacity remaining, resulting in a surplus of batteries with significant potential for reuse. By gaining value from these used batteries in the ancillary services market, the life-cycle costs and environmental impacts for electric vehicles are reduced. Without a secondary market or application for these used batteries, concerns for the environmental consequences and battery replacement cost will grow and hinder electric vehicle market growth.

This project quantifies the effects to battery life and performance for current and future vehicle-to-grid use of plug-in electric vehicle batteries and associated technology in California. The information learned through the research can be useful for developing a compensation strategy for clients willing to offer their assets for use in a vehicle-to-grid application.

Keywords: California Energy Commission, plug-in electric vehicles, vehicle-to-grid, second-life, batteries, lithium-ion, ancillary services, hybrid electric vehicles

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Introduction

The transportation sector accounts for 42 percent of greenhouse gas (GHG) emissions in California. Since 92 percent of all transportation energy comes from petroleum-based fuels according to the Western States Petroleum Association, California can reduce transportation emissions by displacing petroleum-based vehicles with zero-emission electric vehicles. This vehicle displacement will push California closer to achieving its GHG emissions and air quality goals.

The Governor's Zero Emission Vehicle Action Plan set goals of supporting charging infrastructure for one million zero-emission vehicles by 2020 and 1.5 million zero-emission vehicles by 2025; however, the high cost of plug-in electric vehicles remains one of the primary barriers to increased market penetration. One way to potentially offset these costs is to use plug-in electric vehicle batteries as energy sources to enable participation in the electricity grid ancillary services market using a method commonly known as "vehicle-to-grid."

Project Purpose

The Energy Commission tasked Concurrent Technologies Corporation to conduct analysis and produce performance data supporting a vehicle-to-grid use of plug-in electric vehicle batteries and associated technology demonstration in California. A key aspect of this Energy Commission project was coordination and support of the United States Department of Defense (DoD) Plug-In Electric Vehicle Program being demonstrated at Los Angeles Air Force Base and managed by Concurrent Technologies Corporation. The DoD program intended to show improved value for plug-in electric vehicles (PEVs) by demonstrating the benefits of vehicle-to-grid (V2G) technology. With V2G technology, idle vehicles would act as "distributed batteries" for the power grid. Los Angeles Air Force Base would use the vehicles to co-optimize demand response (discharging vehicles to serve building load at times of peak demand) and participating in the California Independent System Operator's ancillary services markets. Once the V2G portion of the demonstration was completed, Concurrent Technology Corporation would evaluate the health of the battery systems and perform testing to determine if batteries are suitable for energy storage in second-use applications such as support to the grid or localized back-up power.

Project Approach

The Department of Defense Plug-In Electric Vehicle Program was responsible for the electric vehicle charging infrastructure design and implementation, equipment, and Fleet Management System required to perform the vehicle demonstration at Los Angeles Air Force Base. Gasoline- and diesel-fueled fleet vehicles were replaced with plug-in electric vehicles and plug-in hybrid electric vehicles. Under anEnergy Commission contract, Concurrent Technologies Corporation provided battery packs and their installation from Electric Vehicles International LLC, VIA Motors Incorporated, and Electric Vehicle Add-on Systems for test and demonstration at Los Angeles Air Force Base. Concurrent Technologies Corporation also provided battery packs from VIA Motors Incorporated and Valance Technology Incorporated for laboratory testing, research and analysis. Under a separate contract, the Energy Commission provided the Nissan LEAFs to use at the Los Angeles Air Force Base.

Project Results

The DoD Plug-In Electric Vehicle Demonstration Program and Energy Commission Vehicle-to-Grid Program confirmed V2G technology can support the DoD non-tactical fleet operations and generate revenue from V2G market participation. However, cost parity with conventional vehicles can only be achieved after V2G equipment is fully commercialized, leading to improvements in system reliability. This program was successful in advancing bi-directional technologies and established valuable infrastructure for sustaining and developing further electric vehicle activities in future years.

Based on the testing performed under this agreement, battery life is reduced when used in V2G applications, but the extent it is reduced varies greatly depending on the overall use profile of the battery, as well as other use and environmental factors. Under specific test conditions, a V2G Pack had a capacity reduction of 25 percent over rated capacity, while a Control Pack had a capacity reduction of 16 percent. On a simplified total energy basis, the rate of degradation for both battery packs was nearly identical. However, when accounting for operating temperature and second-order effects of time, the corrected rate of degradation for the V2G Pack was found to be approximately 19 percent less than the Control Pack.

Results also show that PEV batteries maintain near 80 percent of battery capacity after their useful life in vehicle and vehicle to grid applications. This capacity provides an opportunity for these batteries to be used in a second-life application. This project developed a “determination of condition” protocol which provides an approach to access battery health based on available historical data or post testing. This protocol suggests grouping batteries of similar health to achieve the most potential of remaining battery capacity.

This vehicle-to-grid program did not participate in the California Independent System Operator anxicellary market, however, a follow-on research project is under way and funded by the Energy Commission’s Electric Program Investment Charge (EPIC) program to further explore battery storage. The project will add stationary second-life batteries to the existing PEV fleet site to reduce the overall cost of ownership by maximizing battery lifetime, shifting load to reduce electricity and demand charges, and providing V2G and V2B service, including those supporting using onsite solar generation.

Benefits to California

This project supported California’s Alternative and Renewable Fuel and Vehicle Technology Program and Executive Order B-16-2012 zero-emission vehicles goals by generating and analyzing data to better understand vehicle-to-grid technologies to achieve the state’s climate change policies. The project benefited significantly from collaboration and coordination with, at the time, the largest Department of Defense vehicle-to-grid demonstration project to explore economic value of aggregated plug-in electric vehicle storage and ancillary services to the California grid. The data in this report is useful for developing a compensation strategy for stakeholders and clients willing to offer their assets to use in a V2G application and clients looking to repurpose used electric vehicle batteries. California can use the information from this report to define long-term PEV strategies, proactively working with PEV and EVSE vendors to determine their strategies for bi-directional charging over the next decade.

CHAPTER 1:
Introduction

Project Background

Transportation fuels and vehicles are critical elements in California's economy and society with reports indicated that 96 percent of all transportation energy that Californians consume comes from petroleum-based fuels. To reduce the impact to the environment, including reduced carbon emissions from transportation, the Governor's Zero Emission Vehicle Action Plan (following Executive Order B-16-2012) set goals of reaching 1 million zero-emission vehicles by 2020 and 1.5 million zero-emission vehicles by 2025. To meet these goals, significant changes to the state's fuel and vehicle profiles are necessary. Widespread adoption of plug-in electric vehicles (PEVs) is an integral component to achieving California's low-carbon transportation goals. However, the high cost of PEVs continues to remain one of the primary barriers to increased market use. One way to offset these costs is to use electric vehicle batteries as energy sources for the electrical grid ancillary services (AS) market, commonly known as "vehicle-to-grid" (V2G).

To gather more data regarding the effect of V2G activities on vehicles, the California Energy Commission directed Concurrent Technologies Corporation (CTC) to complement a demonstration of V2G being conducted by the U.S. Department of Defense (DoD) Plug-In Electric Vehicle Program. This DoD demonstration used non-tactical fleet vehicles at Los Angeles Air Force Base (LAAFB), California with goals to:

1. Determine if V2G technology works.
2. Evaluate if V2G supports or interferes with mission operations (learning enhanced by converting all general purpose non-tactical vehicles (NTV) to electric).
3. Determine if / how PEVs can achieve cost parity.

During this demonstration, gasoline- and diesel-fueled fleet vehicles were replaced with PEVs and plug-in hybrid electric vehicles (PHEVs). In addition, these vehicles were modified to be bi-directional with the electrical grid when parked at their charging stations. Bi-directional technology allows the vehicle batteries to be used as energy sources for the AS market and the resulting revenue to offset electric vehicle costs.

Problem Statement

Preliminary analyses of V2G technologies indicated the associated economic benefits would be positive, potentially significant enough to offset higher upfront costs of PEVs. However, V2G technologies and integration have not been demonstrated at a sufficiently large scale to validate the expected economic benefits and encourage fleet and facility operators to consider deploying vehicle-to-grid applications. In particular, impacts to the battery performance should be characterized to validate long-term benefits to the PEV and PHEV owners.

Project Objectives

The project objectives were to produce data supporting current and future V2G use of PEV batteries in California and the associated technology and develop a preliminary design for applying second-life PEV batteries as a stationary energy storage/resource for California utilities. CTC was tasked to leverage the DoD V2G demonstration by procuring electric vehicle battery test materials for use as energy sources during the demonstration. CTC evaluated data collected from the demonstration to provide an analysis of the performance of the battery test materials in V2G activities and identify any long-term performance issues.

Scope of This Report

This report documents the tasks performed under Agreement Number 600-012-016. Chapter 2 summarizes the collaboration and data generated during the DoD V2G demonstration activities on LAAFB. Chapter 3 describes independent laboratory testing of PEV battery system test articles to evaluate the effects of V2G operations. Chapter 4 describes modeling, simulation and analysis that could be used to predict battery life in V2G applications. Chapter 5 discusses the potential for EV batteries repurposing and provides a design concept for a large-scale energy storage system. Chapter 6 discusses conclusions drawn from the project and provides recommendations for California to achieve its goals for zero-emission vehicles.

CHAPTER 2:
LAAFB Field Demonstration Testing and Analysis

The largest nation-wide PEV V2G demonstration was conducted between 2012 and 2014 by the U.S. DoD to better understand the effects of V2G activities on vehicle battery packs. This demonstration was conducted at LAAFB with data collection done May 1, 2016 through April 30, 2017. During this field demonstration, gasoline- and diesel-fueled fleet vehicles were replaced with PEVs and PHEVs. PEVs are fully electric and run completely from energy stored in the vehicle's battery. PHEVs use an internal combustion engine (ICE) and a battery. "Plug-in" refers to a vehicle's ability to recharge by plugging into a charging station connected to the electrical power grid.

Bi-directional charging stations, also referred to Electric Vehicle Supply Equipment (EVSE), were developed and installed along with the associated power distribution infrastructure. These charging stations allow two-way power flow from the vehicle to the grid and from the grid to the vehicle. The charging stations and vehicle battery systems were modified to be bi-directional with the electrical grid while meeting all requirements of the local electrical utility, Southern California Edison. Under the DoD program, PEV battery capacity (energy) was sold to the California Independent System Operator (California ISO), an independent grid operator that manages the flow of electricity across 80 percent of California's power grid. California ISO forecasts electrical demand in short intervals, accounts for availability and acts as a traffic controller to match buyers and sellers of electricity. This allowed the vehicle batteries to be used as energy sources or sinks for the AS market, with the resultant revenue offsetting electric vehicle and infrastructure costs.

Vehicle use was managed through a fleet management system (FMS), a software application developed to reserve and dispatch vehicles. The reservation provided information on the availability of the vehicles to allow the PEV-V2G control software to estimate the available battery capacity of the vehicles connected to the charging stations. This information was used to prepare a day-ahead bid for California ISO that defined available battery capacity in 1-hour increments for a 24-hour day.

When bids were accepted, California ISO provided a real-time demand signal identifying the specific amount of power and direction required. The system consumed the power to charge the batteries (regulation down, consuming excess supply) or used the batteries to provide power back to the grid (regulation up, making up for a supply shortfall). The PEV-V2G control software received the demand signal and provided commands to each individual charging station for a specific power setting to achieve the aggregate power requested by California ISO.

CTC monitored and collected data from vehicle battery system test materials used in the field demonstration. Table 1 details the test materials procured under this program.

Table 1: V2G Battery Test Materials Procured

Vehicle Manufacturer	Battery Chemistry / Vendor	Number of systems procured	Kilowatt-hour (kWh) capacity per battery	Total kWh capacity procured
Electric Vehicles International LLC	$LiFeMgPO_4$ / Valence	4	53.8	215.2
VIA Motors	$LiFePO_4$ / A123 Systems	7	21.1	147.7
Electric Vehicle Add-On Systems (EVAOS)	$1LiFePo_4$ / China Aviation Lithium Battery Co., Ltd (CALB)	5	26.9	134.5

Source: Concurrent Technologies Corporation

The test materials were integrated into vehicles participating in the DoD demonstration. The intent was to monitor how each individual vehicle battery was exercised over the course of the demonstration. Periodic tests were performed to evaluate how the battery's capacity degraded over time in response to this use.

The following sections discuss the technical approach of the field demonstration data collection and analysis effort, including:

- An overview of the vehicles used in the DoD field demonstration and their associated batteries.
- An examination of factors leading to degradation and the differences that vehicles experienced during the demonstration as the result of driving and V2G activities.
- The data analysis method used to quantify and characterize vehicle battery usage, performance and degradation during the field demonstration.
- The analysis conducted on the test data to quantify the time each vehicle spent in various activities and the results of state-of-health (SOH) testing.

LAAFB Demonstration Vehicles

To demonstrate an all-electric general purpose fleet, the fleet consisted of EV's in the following categories: passenger and cargo vans, medium duty box and stake-bed trucks, pick-ups and sedans. These systems were manufactured by Electric Vehicles International LLC (EVI), Nissan, Phoenix Motorcars and VIA Motors (VIA). PEV types and quantities are shown in Table 2, with vehicle type (PEV or PHEV). As indicated, the Energy Commission procured some of the vehicle batteries as part of a contribution to the demonstration.

Table 2: PEV-V2G Vehicles at LAAFB

Manufacturer	Model	Vehicle Quantity	Item Procured By	Vehicle Description
EVI	REEV	4	4 batteries procured under this contract	2 Stake bed truck and 2 box trucks; PHEV
Nissan	LEAF	13	13 vehicles procured under separate contracts	Sedans; PEV
Phoenix Motorcars	Phoenix Shuttle	1	Procured by DoD	Passenger shuttle; PEV
VIA Motors	VTRUX	11	7 batteries procured under this contract (others DoD)	Vans; PHEV
*EVAOS	F-Series trucks modified	5	5 energy storage modules procured under this contract	Ford F-series trucks with aftermarket modifications; PHEV

***Technical issues prevented use of these vehicles.**

Table 3 shows manufacturer specifications for the PEV fleet vehicles. "Rated Capacity" refers to the manufacturer's specified battery capacity.

Table 3: PEV-V2G Vehicle Specifications

Model	Electric Range* in miles	Cargo/Passenger Capacity	Rated Capacity in kilowatt-hours (kWh)
REEV	40 (PHEV)	5,300 pounds (lbs.) payload / 2 seats	54
LEAF	75 (PEV)	5 seats	24
Phoenix Shuttle	100 (PEV)	12 passengers + driver	102
VTRUX Van	32 (PHEV)	2,650 lbs. (cargo van) / 11 passengers + 1 driver (passenger van)	21

***For PHEVs, ICE used only when electric range is exceeded. Only the range associated with battery power is shown in the table.**

Source: Concurrent Technologies Corporation

Vehicle Type Summaries

The following sections provide summaries of each vehicle type used in the field demonstration.

EVI REEV Trucks

Four PHEV trucks were procured from Electric Vehicles International LLC and were prototypes of EVI's Range Extended Electric Vehicle (REEV) model. REEV trucks were built on a Ford F-550 chassis using EVI's custom drive system. They were PHEVs capable of operating in a fully electric mode, only utilizing the ICE when the vehicle battery was discharged. Two REEVS were stake bed trucks with lift gates, which provided capacity to haul local cargo loaded by dolly, forklift or from a dock. The other two were box trucks, which provided base personnel with medium-sized enclosed cargo movement capabilities. The battery system was installed in the bed of the truck reducing the available cargo space as compared to the ICE counterpart.

Nissan LEAFs

Thirteen Nissan LEAF PEV sedans were utilized during the demonstration. Thirteen LEAFs were procured by the California Energy Commission under a separately funded program, however one of these vehicles was involved in an accident and totaled in February 2016. This totaled vehicle was replaced by a LEAF provided by the DoD demonstration in April 2016. All of these sedans were 2012 model year and procured as used vehicles in various trim models. Nissan North America provided a software patch that enabled bi-directional charging. (This software is now standard on model year 2013 LEAFs and newer.) The LEAFs were used for a variety of short range day trip applications by base personnel.

Phoenix Shuttle

One Phoenix shuttle was used during the demonstration. This was an early production run vehicle built using an El Dorado Aerotech chassis, built on the Ford E350 cutaway cab. The Phoenix shuttle was outfitted with accessories such as power outlets and overhead luggage racks. Primary use was as a regular mass transit circular route around the base, picking up and dropping off personnel. The shuttle typically ran 40 to 50 miles, or approximately six transit loops, per day. As a secondary application, the shuttle was used to transport dignitaries to and from the airport on an approximately monthly basis.

VIA VTRUX Vans

Eleven VTRUX vans manufactured by VIA Motors were used during the demonstration. VTRUX vans were built on the chassis of a Chevrolet Express 2500. They were PHEVs capable of operating in a fully electric mode, only utilizing the ICE when the vehicle battery was exhausted. Ten vans were in the passenger configuration, which could accommodate 11 passengers and the driver, while the remaining van was in the cargo configuration, with its rear space cleared for cargo transport. Many of the passenger vans were used on a regular mass transit circular route around the base, picking up and dropping off personnel. These vans were often driven almost 100 miles, or up to 13 transit loops, during the day. The vans were typically not charged mid-mission, meaning that the vans would transition to running on ICE after exceeding their electric-only range. The cargo vans and passenger vans were also used in a variety of day trip applications.

Vehicles at Demonstration Start

The EVI REEV, Phoenix Shuttle and VIA VTRUX vehicles were prototype production runs manufactured specifically for the PEV-V2G program, with limited pre-demonstration usage. The Nissan LEAF sedans were commercial vehicles purchased from the used vehicle aftermarket. Therefore, the Nissan LEAF batteries experienced some capacity loss from rated specification due to regular driving activities prior to the demonstration. Vehicle use for a one-year demonstration period was analyzed—May 1, 2016 through April 30, 2017. Table 4 shows the following information about each vehicle:

Table 4: Test Vehicle Information

Type	Vehicle ID	Site Arrival Date	Arrival Mileage	Demo Start Mileage	Demo End Mileage
Nissan LEAF Sedans	12B80011	Oct 11, 2013	7,389	10,336	11,934
	12B80012	Oct 11, 2013	5,940	9,517	11,772
	12B80013	Oct 11, 2013	7,140	10,098	12,631
	12B80014	Oct 11, 2013	4,945	7,773	10,518
	12B80015	Oct 11, 2013	6,601	10,023	12,379
	12B80016	Oct 11, 2013	4,576	6,961	7,534
	12B80018	Oct 11, 2013	3,282	5,148	8,322
	12B80019	Oct 11, 2013	4,011	7,685	10,486
	12B80020	Oct 11, 2013	4,226	6,492	7,692
	12B80021	Oct 11, 2013	5,790	8,395	9,386
	12B80022	Oct 11, 2013	9,069	10,627	11,471
	12B80023	Oct 11, 2013	4,326	6,529	10,706
	12B80024*	April 15,2016	1,716	1,716	1,764
VIA VTRUX	044M580	Sep 30, 2015	<500	1,026	3,784
	042M778	Sep 30, 2015	<500	1,581	4,635
	14Z10424	Sep 30, 2015	<500	2,565	3,665
	14Z10425	Sep 30, 2015	<500	1,855	5,651
	14Z10426	Sep 30, 2015	<500	1,010	1,886
	14Z10427	Sep 30, 2015	<500	2,058	4,477
	14Z10429	Sep 30, 2015	<500	6,265	10,125
	14Z10430	Sep 30, 2015	<500	1,313	9,271
	14Z10431	Sep 30, 2015	<500	1,633	8,689
	14Z10432	Sep 30, 2015	<500	2,322	4,792
	14Z10433	Sep 30, 2015	<500	361	777
EVI REEV	14B80133	Mar 18, 2015	<500	2,788	2,949
	14B80134	Apr 1, 2015	<500	13,476	13,514
	14B80135	May 27, 2015	<500	1,153	1,236
	14N80136	June 8, 2015	<500	6,598	6,687
Phoenix Shuttle	14Z10434	Jan 15, 2015	<500	4,818	11,500

***LEAF 12B80024 was a replacement for a wrecked vehicle and experienced no driving for the majority of the demonstration due to delays obtaining a federal license plate.**

Source: Concurrent Technologies Corporation

The primary purpose of the DoD demonstration was to test the viability of V2G with PEVs. Consequently, the demonstration personnel did not focus on recording every charge and discharge from individual vehicle batteries as the V2G system was tested and brought into service. Limited market participation began as early as October 2015. This means that all vehicles underwent driving, charging and discharging activities before the formal beginning of the V2G test period, and those activities are not included in this analysis. Therefore, vehicle battery degradation from the new as-manufactured rated specification likely occurred during these activities.

Bi-directional Inverters

V2G operation requires a bi-directional inverter to act as the power interface between the alternating current (AC) electrical grid and the direct current (DC) battery. One significant factor in selection of charging stations was the location of the bi-directional inverter. In the case of DC-connect PEVs, the inverter is located inside the EVSE, and energy flows to and from the vehicle's battery pack through a DC power connection to the EVSE. In the case of AC-connect PEVs, the bi-directional inverter is located on-board the vehicle, with an AC connection to a simpler charging station. Vehicle types used in this demonstration were connected as follows:

- Phoenix shuttle bus – DC-connect PEV
- EVI REEV – DC-connect PHEV
- VIA vans – AC-connect PHEV and on-board bi-directional inverter
- Nissan LEAF sedans – DC-connect PEV.

As detailed in the Analysis Methodology Section, much of the data collected during the demonstration came from monitoring power flow through the inverters. For the Phoenix, EVI trucks and LEAFs, the inverter was located inside the charging station, and inverter data were correlated to a specific vehicle by tracking which vehicle was connected for each transaction. For the VIA vans, each van had its own on-board inverter whose data were queried and tracked through the on-board communications system.

Factors Leading to Battery Degradation

To truly understand potential degradation resulting from V2G participation, it is important to investigate the factors leading to battery degradation and how they relate to vehicle battery use during the monitored demonstration period. Degradation of lithium-ion cells depends on calendar aging and the number of cycles, as well as operational conditions such as use, depth of discharge (DOD) and temperature. To provide context for data analysis, the following sections summarize these factors and how each vehicle battery pack may have been impacted by these factors.

Calendar Aging

The aging process leading to battery degradation, with the exception of battery usage (cycles), is referred to as calendar aging. Calendar aging prior to the V2G demonstration period is not well documented for these vehicles. Although the date of manufacture for the Nissan LEAFs can be approximated from their model year and for the other vehicles based on their delivery date, no specific information was available from vendors regarding when vehicle battery packs were assembled or at what temperature they were stored prior to May 1, 2016. For this analysis, calendar aging during the one-year demonstration could not be isolated from the battery cycling based on several factors such as previous battery use.

Cycles

A battery cycle is commonly understood as the complete discharge of a fully charged battery with a subsequent recharge. Battery manufacturers provide cycle life projections as the number of cycles at a given C-rate, a measure of the rate at which a battery is charged/discharged relative to its maximum amp-hour capacity, DOD and temperature until battery capacity drops to 80 percent of the rated capacity. This is difficult to correlate with actual usage because most cycles do not follow this identical pattern, but it does provide a reference. Batteries are usually operated under partial discharges of varying depth before being completely (or in some cases only partially) recharged.

Use (Total Energy)

Another factor in battery degradation is usage or total energy. This is the total energy (typically given in watt-hours) removed from or added to the battery. As a battery is charged and discharged, electrode materials swell and contract causing the battery components to weaken. Usage was a factor tracked in detail during the V2G demonstration, and total energy removed or added to vehicle batteries on a daily basis during specific use cases will be assessed in the Analysis Methodology Section.

Depth of Discharge

The depth of discharge (DOD) is a measure in percentage of the amount of energy discharged relative to the current battery capacity. By definition, its value plus the state of charge (SOC) must total 100 percent. For example, if the SOC is 80 percent, the DOD is 20 percent. Batteries experience more degradation and shorter life when experiencing higher DOD. In some cases, reducing DOD from 100 percent to 80 percent can double the cycle life of a battery. The DOD for each vehicle battery during each use case was tracked on a daily basis during the V2G demonstration and will be evaluated in the Analysis Methodology Section.

Temperature

Temperature has a strong impact on the degradation of lithium-ion batteries. Most battery corrosion occurs during charge/discharge cycles. The rate of corrosion increases at higher temperatures. The best cycle life can be obtained at moderate temperatures. The maximum pack temperature experienced by each vehicle battery during various use cases was recorded and will be considered in the Analysis Methodology Section.

Analysis Methodology

Proper quantification and characterization of vehicle battery performance is reliant on a determination of unique vehicle use instances throughout the evaluation period and a compilation of vehicle performance data for each of the identified usage instances. This section describes the analysis conducted on demonstration data gathered between May 1, 2016 and April 30, 2017. Information about analysis methodology and data sources is provided in the following sections.

Use Cases

Vehicle battery activity fall into six "use cases," which describe the type of activity engaging the vehicle battery— driving, V2G, cell balancing, battery health tests, other and unknown. These use cases were used extensively in the analysis to show the vehicle battery charge/discharge activity due to regular PEV driving and charging compared to V2G.

Driving

This use case represents time while the vehicle was being driven, as well as any time the vehicle was active and not connected to a charging station (e.g., idle time). An on-board data collection system was used to capture this information for all vehicles participating in the demonstration. While the majority of battery activity during driving was discharge, some charging occurred as a result of regenerative braking returning energy to the vehicle battery or when the ICE was engaged on PHEVs.

V2G

This use case represents time when the vehicle was participating in the V2G market. These events typically took place in hour-long intervals. While market participation treated the entire PEV fleet as a single energy source, matching individual vehicle data against time of participation allowed a determination to be made of how much energy was charged and discharged from each specific vehicle battery.

Cell Balancing

Cell balancing represents an activity conducted periodically to ensure charges between individual cells of the vehicle battery were kept balanced. Typically, PEVs carry out cell balancing while connected to EVSEs according to the programming of their battery control systems. However, during V2G system development, it was determined that cell balancing of the EVI REEVs and the Phoenix Shuttle could interfere with V2G activity and force the vehicles out of market participation. Therefore, they were given designated periods of time during which the battery management systems could conduct cell balancing and were otherwise not allowed to enter cell balancing mode. This time period is represented by the use case Cell Balancing.

This use case does not apply to Nissan LEAF sedans or the VIA vans. The cell balancing of LEAFs did not interfere with V2G activities, and LEAFs were therefore allowed to cell balance freely. LEAF cell balancing can be assumed to be occurring during the "other" use case for LEAF sedans. VIA did not implement cell balancing before the conclusion of the demonstration, so no activity was recorded under any use cases.

Battery Health Tests

Battery health tests, also known as state-of-health (SOH) tests, were conducted for vehicle batteries on a monthly basis, depending on equipment availability. During SOH testing, fully charged vehicle batteries were discharged to a minimum threshold while measuring the amount of energy removed from the batteries. This process quantified pack energy capacity and provided a means of assessing degradation and projecting battery performance. SOH tests made up a small percentage of total vehicle battery activity, but they are characterized as a separate use case since SOH charging and discharging would not be required under standard PEV or V2G usage.

Grid Connected

This use case represents normal charging and discharging when the PEV was connected to an EVSE. It included charging the battery after a driving mission, bringing the battery to a specific level of charge in preparation for market participation, sitting connected to an EVSE with no charging or discharging occurring, and any charge or discharge activity with an unidentified purpose.

Unknown – no data

This use case represents time periods for which no data were available. This use case included times when the PEV was turned off while not connected to an EVSE, with the expectation that the vehicle battery was not undergoing any activity. In some cases, it may also represent a failure of the on-board data collection system.

Data Sources

To identify the above categories of vehicle use, the following types of data were collected throughout the demonstration period between May 1, 2016 and April 30, 2017.

- **Driving Data** – This information detailed how each vehicle was utilized during driving activities. Information included trip duration, mileage, driving conditions, and any charge/discharge of the vehicle battery while the vehicle was moving.
- **V2G Market Participation** – This information covered V2G market participation for the fleet as a whole and how each individual vehicle battery was utilized during regulation up and regulation down activities.
- **Stationary Non-V2G** – This information included activities while connected to LAAFB charging stations not related to V2G. This includes normal charging/discharging, preparation for market participation, cell balancing, battery health tests and miscellaneous use.

Two data collection devices were used to gather this information—the On-base Electric Vehicle Infrastructure (OB-EVI) and FleetCarma On-Board Data Collection (OBDC). Table 5 shows the information derived from these two sources and the data types they provided. These data sources are discussed in more detail in the following sections.

Table 5: Data Categories

Source	Data Category	Driving	V2G Market Participation	Stationary Non-V2G
OB-EVI	Inverter Readings		X	X
	CAISO Dispatch Results		X	
	Battery Health Test			X
	Cell Balancing			X
FleetCarma OBDC	Trip Reports	X		
	Charge Reports		X	X
	Real-Time Data	X	X	X

X – Data Available

Source: Concurrent Technologies Corporation

OB-EVI

The transition from conventional vehicles to a PEV fleet required a fundamental change in fleet management strategies. Primarily, the fleet manager needed to maintain cognizance of the charge state of each PEV battery, as well as the range capabilities of each PEV at all times to dispatch vehicles properly. Integrating V2G activities into a PEV fleet created additional layers of complexity. In a V2G model, the PEV was treated as an energy asset in addition to its traditional role as a mobility asset. Information regarding the PEV charge state and range capabilities must be integrated with energy data from the facility and public electrical grid to optimize the PEV's energy functions without diminishing its primary mobility requirements.

The OB-EVI software architecture was implemented at LAAFB to manage the PEV fleet, control inverter activity and bi-directional power flow, and perform the activities required for participation in CAISO's ancillary services market. Key OB-EVI modules were the fleet management system (FMS) and the charge control module (CCM).

- The FMS was designed to support military base transportation scheduling by providing an automated solution for dispatch personnel to administer reservations and input requests to drive PEVs on or off the base. The FMS managed vehicle schedules based on current battery state to ensure a PEV had a sufficient stored energy for driving activities.
- The CCM managed the charging and discharging of individual vehicles, preparing them for scheduled trips and meeting the CAISO charge/discharge requirements. This module also tracked which vehicles were plugged into charging stations and the actual SOC for each vehicle.

Four types of OB-EVI data were gathered and analyzed for this report—inverter data, CAISO dispatch results, battery health test data and cell balancing data.

Inverter Readings

The OB-EVI monitored and recorded the activity of the bi-directional inverters used to charge and discharge the demonstration vehicles. By tracking the duration and power of inverter activity, energy transfers to and from the vehicle battery by the LAAFB charging infrastructure were recorded. As noted in the LAAFB Demonstration Section, these inverters were located either on the vehicle itself, in which case all activities of that inverter were automatically matched to a particular vehicle battery, or on the charging station, in which case, periods of inverter activity were associated with the connected vehicle.

California ISO Dispatch Results

Dispatch results recorded OB-EVI's response to CAISO charge/discharge requests during V2G market participation. These results did not describe the activities of any individual vehicle battery. Instead, they recorded energy transfer from the virtual battery created by all vehicles participating in a V2G market during a particular dispatch period. By matching a vehicle's inverter activity against these dispatch results, it was possible to determine the participation of each individual vehicle battery pack in the overall CAISO dispatch.

Battery Health Tests

Battery health test data included inverter readings for a given battery during time periods when the battery was involved in battery health test runs, which were executed monthly (beginning in October 2016) to assess the performance of each battery pack. Tests were only executed if both the vehicle and its associated EVSE were operational and communicating with the OB-EVI system.

Each successful battery health test included the following steps:

- Charge the battery to 100 percent SOC and cell balance if needed
- Discharge the battery to 20 percent SOC
- Charge the battery to 100 percent SOC.

A discharge limit of 20 percent SOC was used, as draining a battery to 0 percent SOC can have detrimental effects on vehicle batteries. SOC was as reported by the vehicle's own battery management system. By monitoring battery energy discharged from 100 percent to 20 percent SOC (as reported by the vehicle), battery capacity could be determined. Changes in discharged energy under the same procedure indicated any battery degradation.

Key data collected for vehicles undergoing a SOH test were the inverter readings within each test run.

Cell Balancing

The server-commanded cell balancing process included the following steps:

- Fully charge the battery to 100 percent SOC
- Conduct cell balancing.

The data collected during server-commanded cell balancing was identical to data described in "OB-EVI Inverter Readings" Section.

FleetCarma

The PEV-V2G demonstration included the procurement, installation and operation of FleetCarma vehicular OBDC for all V2G vehicles, along with the installation of supporting data transfer and data archival infrastructure to facilitate retrieval of collected vehicle performance data. The data included battery SOC, battery voltage, battery current, battery temperature, ambient temperature, fuel usage, average daily distance, total distance, idle time, vehicle speed and energy use. Each vehicle was equipped with OBDC, also known as a FleetCarma data logger, to collected vehicle performance data every second during vehicle driving and charging activities. The data was used to quantify the performance capabilities of PEV-V2G vehicles to support driving missions and participate in utility ancillary services markets.

Three types of FleetCarma reports were produced for each vehicle—trip reports, charge reports and real-time data.

- FleetCarma Trip Reports – Identified time periods when each vehicle was being driven and recorded energy usage during these periods.
- FleetCarma Charge Reports – Identified time periods when each vehicle was charging at an EVSE and recorded energy usage during these periods.
- FleetCarma Real-Time Data Reports – Recorded vehicle performance data once per second for any vehicle being charged or driven, and included periods of vehicle inactivity when no charging or driving occurred.

Report Types

Based on these collected data, CTC generated four summary reports for analysis:

- Report 1 – Use Summary Report
- Report 2 – Categorical Maximum DOD Report
- Report 3 – SOH Capacity Report
- Report 4 – Energy Report.

Each report is described and discussed in detail in the data analysis discussion.

Report 1 – Use Summary Report

The Use Summary Report provided a usage profile for each demonstration vehicle over the one-year demonstration period, showing the percentage of total time the vehicle was in each use case and the percentage of total energy transferred to and from the vehicle battery for each use case. For this report, energy transfer is direction neutral (e.g., 1 kWh of charging and 1 kWh of discharging equal 2 kWh of energy transfer).

Report 2 – Categorical Maximum DOD Report

The Categorical Maximum DOD Report was generated on a per-day time horizon, combining all instances of each use category into a total for the day. The maximum DOD and data related to the pack and ambient temperature were calculated for each use case. As DOD and pack temperature are two significant contributors to battery degradation, these data were analyzed to determine which use categories consistently placed the greatest stress on the vehicle battery over time.

Report 3 – SOH Capacity Report

The SOH Capacity Report summarized data collected from SOH testing to reliably and consistently determine the remaining energy capacity of the vehicle batteries and to quantify degradation over time. Key data elements included discharge energy and pack temperature statistics.

Report 4 – Energy Report

The Energy Report was used to summarize total energy transfer statistics for each vehicle for each day of the demonstration. For each vehicle and day, energy transfer was further summarized by use category and data source. This report provided fleet-level insights, such as usage profiles and equipment availability during the demonstration.

Timeline

To generate the reports identified, which facilitated performance analysis of the field demonstration system, a timeline concept was used to categorize energy use for every second of the one-year V2G field demonstration by use case for every vehicle. The goal was to understand vehicle usage at all times during the demonstration (i.e., 24/7/365). A complete chronological timeline was developed for each vehicle and was comprised of multiple event entries. Each event entry identified details regarding a chronological segment of vehicle use and described the use category, starting and ending date and time, and the following key data elements from both data sources (OB-EVI and FleetCarma):

- Charge and discharge energy.
- Pack temperature minimum, maximum and average.
- Ambient temperature minimum, maximum and average.
- SOH test status, discharge energy and associated pack temperature minimum, maximum and average.
- Maximum DOD and associated pack temperature.

Data Analysis

Report 1 – Use Summary

The Use Summary Report provided a summary of energy and time usage across each use case for each demonstration vehicle during the one-year demonstration period. Using these data, graphs were generated summarizing average energy use and average time use for each vehicle in the V2G demonstration. The following sections provide summaries of these data for each vehicle type including a driving profile for each vehicle type to help understand the primary mission and use of the vehicles. These driving statistics are derived from FleetCarma trip reports and FMS trip data for trips greater than one mile.

The following notes are provided to help understand the data presented in the sections below.

- A key difference in these data sources is the definition of a trip. In the FMS, a trip is typically defined as a round-trip, encompassing the total time and distance used to drive to a destination and back to the base. FleetCarma, on the other hand, defines a trip as the period between when the vehicle is turned on and when it is turned off. Thus, a vehicle used by base security, which drives from building to building and is turned off while a security check is performed, may be reported as six or more trips in FleetCarma, but only one trip in the FMS. One round-trip to an off-base location in the FMS may be reported as at least two trips in FleetCarma, with additional trips logged if driving occurred after arrival at the destination. A combination of the two sources is needed to understand the true vehicle profile.

- To understand ways in which the other and unknown use categories are applied, consider the previous examples. The time when a vehicle is turned off would be categorized as unknown use, with no data collected. If, however, a vehicle was plugged into a uni-directional charging station at an off-base location, energy data would be collected by the FleetCarma data logger and categorized as other use.

Nissan LEAFs

The Nissan LEAF sedans were passenger vehicles available via the vehicle pool and assigned to individual units. They were used primarily for short, local trips and trips to Fort MacArthur, a DoD site associated with LAAFB where uni-directional charging stations were available to charge vehicles, but not included as part of the LAAFB OB-EVI. Table 6 provides driving statistics for the Nissan LEAFs using FleetCarma and FMS trip data for trips greater than one mile. Figure 1 summarizes average energy use for the Nissan LEAFs, and Figure 2 summarizes average time use.

Table 6: Nissan LEAF Driving Profile for Trips Greater than One Mile

Vehicles Managed	13 – Vehicle Pool + Assigned to Units	
Average Trip Distance	8.61 miles	
Average Trip Duration	**Driving Time**	**Idle Time**
	16.27 minutes	6.96 minutes
Total Trips	2,619	
Count of Trips <= 20 Miles	2,378	
Most Frequent Destination > 20 Miles	Fort MacArthur	

Source: Concurrent Technologies Corporation

Figure 1: LEAF Energy Use Summary

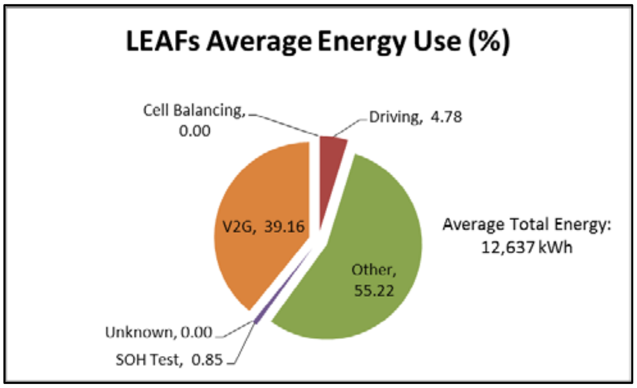
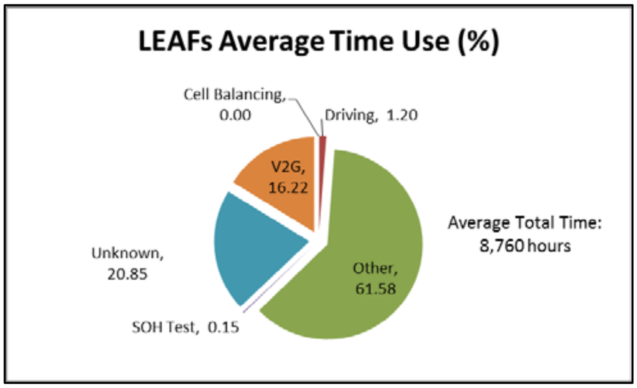


Figure 2: LEAF Time Use Summary



Source: Concurrent Technologies Corporation

The following insights can be drawn from these statistics and graphs regarding vehicle use.

1. Cell Balancing – LEAF cell balancing was neither controlled nor monitored by the PEV-V2G software.
2. Driving – LAAFB primarily used the Nissan LEAFs for short, local trips. A total of 2,619 trips greater than one mile in distance were logged by FleetCarma, but only 1.2 percent of LEAF use time was attributed to driving. Based on fleet requirements, these vehicles weren't driven very much.
3. V2G – Nearly forty percent of the battery energy was used for V2G which accounted for 16 percent of the time.
4. Other – The LEAFs, all-electric vehicles with relatively small battery capacity, spent a majority of the demonstration charging and preparing for market participation.
5. Unknown – no data – Over 60 percent of the time on average, these vehicles were not collecting data which most likely represents the time when the vehicle was off at each trip destination.

EVI REEV Trucks

The EVI REEV trucks were cargo transportation vehicles available through the vehicle pool, used primarily for short, local trips. Table 7 provides driving statistics for the EVI REEVs using FleetCarma and FMS trip data for trips greater than one mile. Figure 3 summarizes average energy use for the EVI REEVs, and Figure 4 summarizes average time use.

Table 7: EVI REEV Driving Profile for Trips Greater than One Mile

Vehicles Managed	4	
Average Trip Distance	2.5 miles	
Average Trip Duration	**Driving Time**	**Idle Time**
	14.94 minutes	33.05 minutes
Total Trips	65	
Count of Trips <= 3 Miles	53	
Most Frequent Destination	On-Base Use	

Source: Concurrent Technologies Corporation

Figure 3: EVI Energy Use Summary

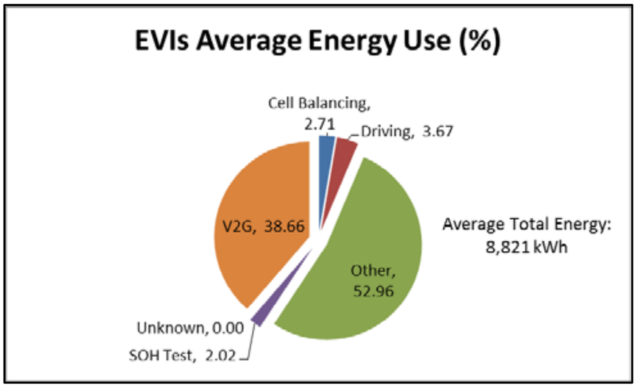
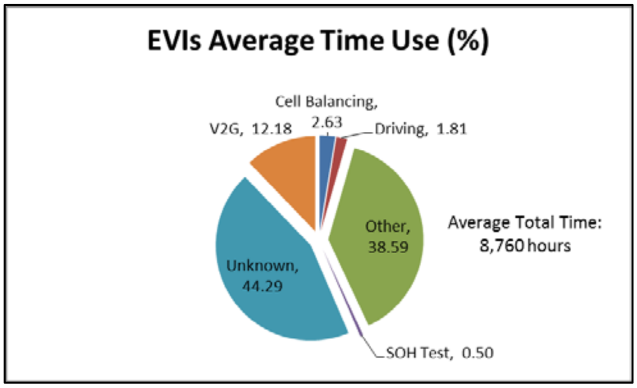


Figure 4: EVI Time Use Summary



Source: Concurrent Technologies Corporation

The following insights can be drawn from these statistics and graphs regarding vehicle usage.

1. Cell Balancing – REEV cell balancing was allowed by PEV-V2G software every three days for a 6-hour period. While this should have yielded approximately 8 percent of time spent cell balancing, frequent downtime of EVI REEVs and their paired EVSEs meant this cell balancing was not always conducted and kept average cell balancing time below 3 percent.
2. Driving – technical issues with the EVI REEVs vehicles resulted in significant down time in some cases for weeks or months at a time. Vehicle 14B80134 was permanently removed from driving missions due to a power steering issue on October 28, 2016 and vehicle 14B80136 was similarly removed from service due to a charging fault on February 28, 2017. Based on these issues, even trucks available for driving missions were generally restricted to on base and almost never used for long-distance transport.
3. V2G – Nearly forty percent of the energy transferred to or from the battery was used for V2G while only 12 percent of the time was spent in V2G.
4. Other – EVI REEVs spent a large amount of time on charging stations not engaged in V2G activity.
5. Unknown – On average, the EVI REEVs spent 44 percent of the total demonstration time off and in an unknown state with very little time parked during driving missions. The

majority is likely times when vehicles were out of service or were not connected to an EVSE due to their paired EVSE being out of service.

Phoenix Shuttle

The Phoenix shuttle was a passenger transport vehicle assigned to specific missions by the vehicle manager. The most frequent mission was a regular mass transit circular route around the base, picking up and dropping off personnel. Generally, the shuttle would be given a half shift of six loops in this service, traveling 40 to 50 miles, and then returned to its EVSE for recharge. Table 8 provides driving statistics for the Phoenix shuttle using FleetCarma and FMS trip data for trips greater than one mile. Figure 5 summarizes energy use for the Phoenix shuttle, and Figure 6 summarizes time use. Note that unlike other vehicle models, only a single Phoenix shuttle operated in the fleet.

Table 8: Phoenix LEAF Driving Profile for Trips Greater than One Mile

Vehicles Managed	1	
Average Trip Distance	10.56 miles	
Average Trip Duration	**Driving Time**	**Idle Time**
	38.35 minutes	22.13 minutes
Total Trips	641	
Count of Trips <= 10 Miles	426	
Most Frequent Destination < 10 Miles	Intra-Facility Shuttle Loops	

Source: Concurrent Technologies Corporation

Figure 5: Phoenix Energy Use Summary

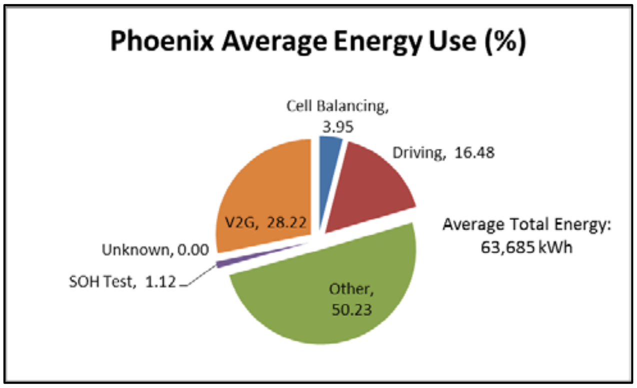
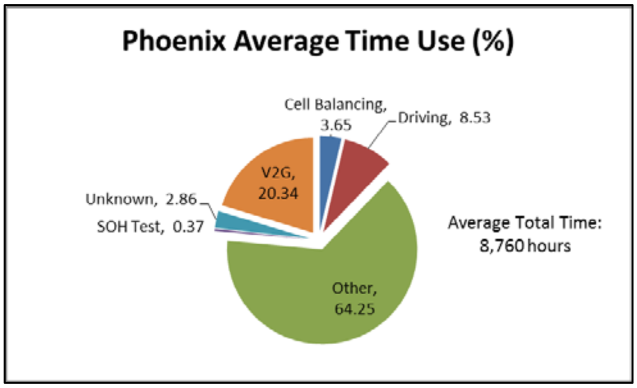


Figure 6: Phoenix Time Use Summary



Source: Concurrent Technologies Corporation

The following insights can be drawn from these statistics and graphs regarding vehicle use.

1. Cell Balancing – The Phoenix shuttle spent less than 4 percent of its time in cell balancing, PEV-V2G software would have allowed it more time if required. Regular use in driving missions and charging on EVSEs likely ensured the vehicle battery pack was able to achieve cell balancing in a timely manner during allowed periods.
2. Driving – As noted, the Phoenix shuttle was regularly used on intra-facility transit loops, explaining the high number of trips under 10 miles for a single vehicle.

3. Other – This category represents 64 percent of the shuttle's time while unknown time is less than 3 percent, indicating that the shuttle spent almost all its time either in active use or connected to an EVSE.
4. Unknown – The Phoenix shuttle was reliably available for service and had comparatively few technical issues, meaning that there was little of the unknown category due to equipment downtime.

VIA VTRUX Vans

The VIA VTRUX vans consisted of 10 passenger vans and one cargo van (no seats in rear) available via the vehicle pool. Several of the vans were assigned to a regular mass transit circular route around the base, picking up and dropping off personnel. Generally, a van on this transit route would be given a full shift in which it would travel almost 100 miles, or up to 13 transit loops, during a day. Note that many vans were frequently out of service due to technical issues or not needed for a transit route on any given day. Table 9 provides driving statistics for the VIA VTRUX vans using FleetCarma and FMS trip data for trips greater than one mile. Figure 7 summarizes energy use for the VIA vans, and Figure 8 summarizes time use.

Table 9: VIA Driving Profile for Trips Greater than One Mile

Vehicles Managed	11 – Vehicle Pool	
Average Trip Distance	11.11 miles	
Average Trip Duration	**Driving Time**	**Idle Time**
	41.74 minutes	20.91 minutes
Total Trips	2,935	
Count of Trips <= 10 Miles	1,967	
Most Frequent Destination < 10 Miles	Intra-Facility Shuttle Loops	

Source: Concurrent Technologies Corporation

Figure 7: VIA Energy Use Summary

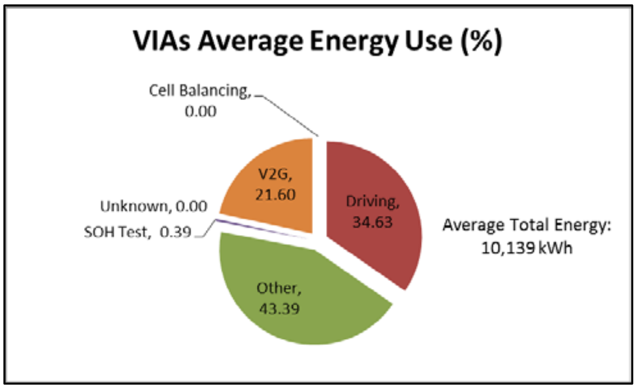
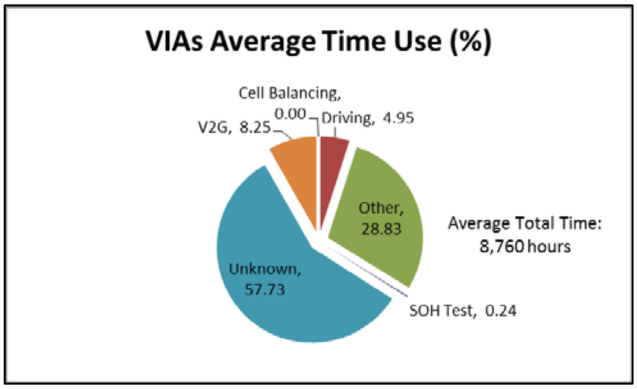


Figure 8: VIA Time Use Summary



Source: Concurrent Technologies Corporation

The following insights can be drawn from these statistics and graphs regarding vehicle use:

1. Cell Balancing – VIA van cell balancing was neither controlled nor monitored by the PEV-V2G software.
2. Driving – On average, these vehicles were not regularly used for driving in comparison with the Nissan LEAFs. Some vans spent less than 2 percent of their time on driving activities, while one van (14Z10430) regularly used in the transit loop spent over 13 percent of its time driving. The large variability was further complicated by the amount of vehicle downtime due to technical issues.
3. Other – Time spent on Other and V2G activities was reduced by the amount of time several of the vans spent in Unknown activities, primarily due to technical issues. See Unknown for more details.
4. Unknown – VIA vans spent a large amount of time disconnected from the EVSE and in the Unknown category even when parked in the EV parking lot. Repeated technical issues caused VIA vans to go into unrecoverable faults that put them into the unknown category. An unrecoverable vehicle fault is defined as a situation in which the van's control system detects some change in the power quality it is receiving from its EVSE that triggers an error code. The control system then disconnects the van from the EVSE to prevent any potential damage. The faults are deemed "unrecoverable" because the van will not clear the fault and reconnect to the EVSE without manual operator intervention (as opposed to "recoverable" faults where the fault will time out and the van will reconnect itself with no outside intervention). Even though vans in unrecoverable faults are physically connected to the EVSE, electrical and data connection is not active so they were considered to be in the "Unknown" category.

   As with the Driving use category, an average of the Unknown use is not as useful for VIA vans due to the high variability in performance. Some vans such as 44M580, 042M778 and 14Z10425 were effectively removed from the demonstration by the end of January 2017 due to immediate unrecoverable faults whenever a charging session was initiated, making the majority of their time classify as Unknown and making the percentage of their time spent on unknown much higher than average. Others vans, such as 14Z10431, were utilized in driving missions and market participation throughout the demonstration and consequently had a much lower percentage of unknown time than the average.

Report 2 – Categorical Maximum DOD Report

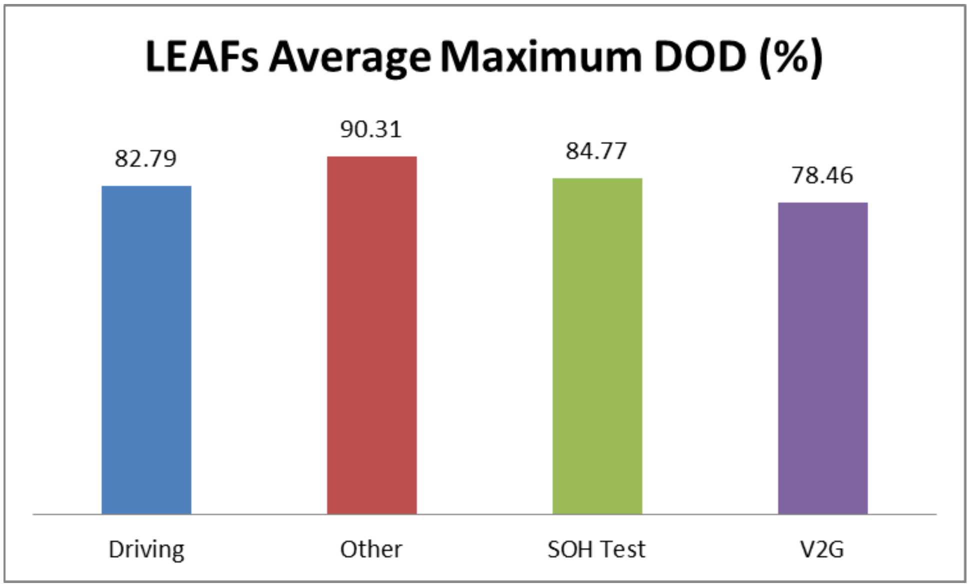
The Categorical Maximum DOD Report was generated on a per-day basis regardless of use category. The maximum DOD and data related to the pack and ambient temperature were identified for each use case. As DOD and pack temperature are two significant contributors to battery degradation, the data was investigated to determine which use categories consistently placed the greatest stress on the vehicle battery over time.

The following four sections describe the average maximum DOD for each vehicle type over the demonstration period. These data were of interest to obtain an understanding of the DOD for each use case.

Nissan LEAFs

Figure 9 shows the average DOD for each of the pertinent use categories. For the LEAFs, the "Other" category had the largest DOD at 90 percent, followed sequentially by SOH test, driving and V2G. From the DOD perspective, V2G use profile was the least aggressive.

Figure 9: Nissan LEAFs Day-by-Day Average Maximum DOD

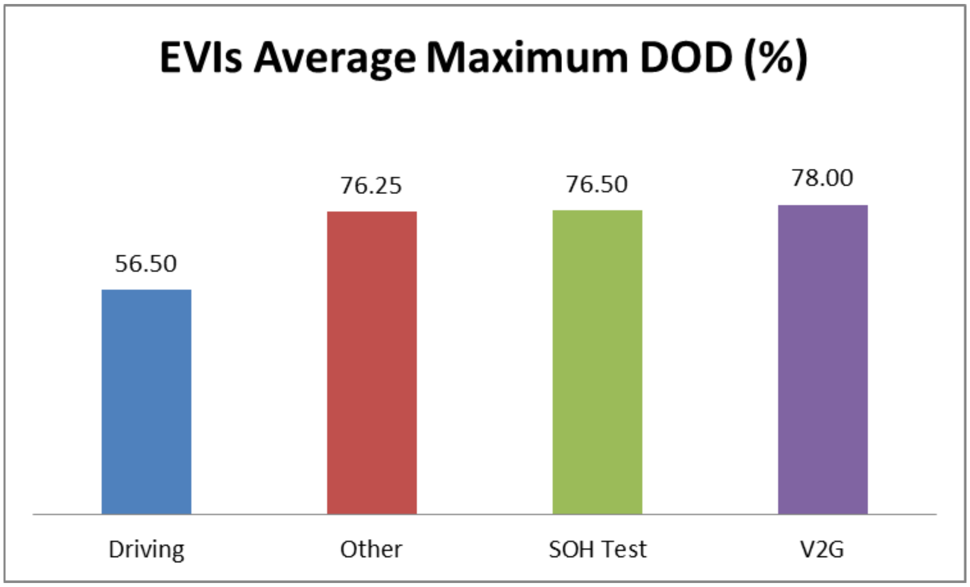


Source: Concurrent Technologies Corporation

EVI REEV Trucks

Figure 10 depicts the average DOD for the EVIs during the demonstration. For this vehicle V2G represents the largest DOD closely followed sequentially by SOH test, other and driving.

Figure 10: EVIs Day-by-Day Average Maximum DOD

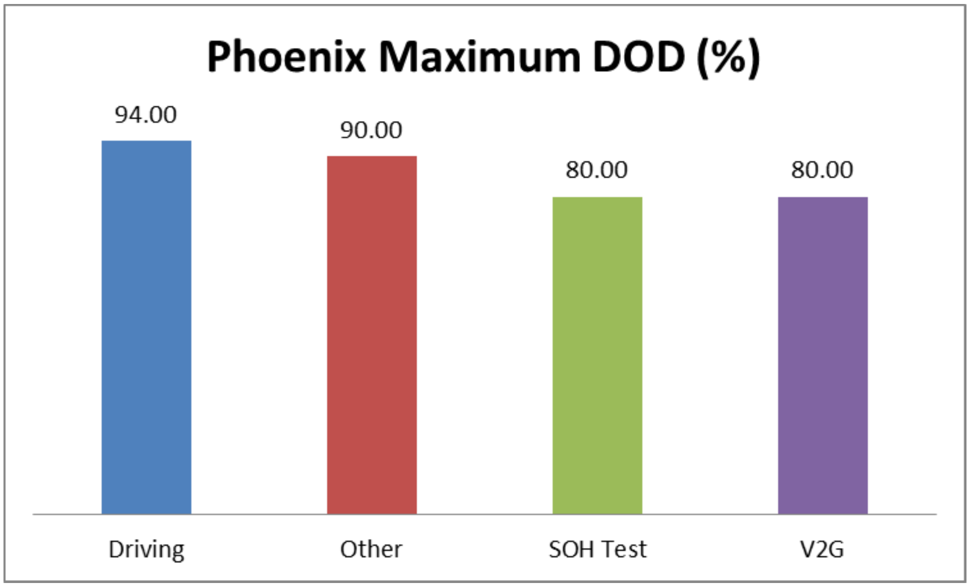


Source: Concurrent Technologies Corporation

Phoenix Shuttle

Figure 11 shows Phoenix Shuttle driving use case had the largest DOD followed by the other use case. Both the SOH test and V2G had the lowest DOD at 80 percent. For this vehicle, the driving case was the most aggressive.

Figure 11: Phoenix Day-by-Day Average Maximum DOD

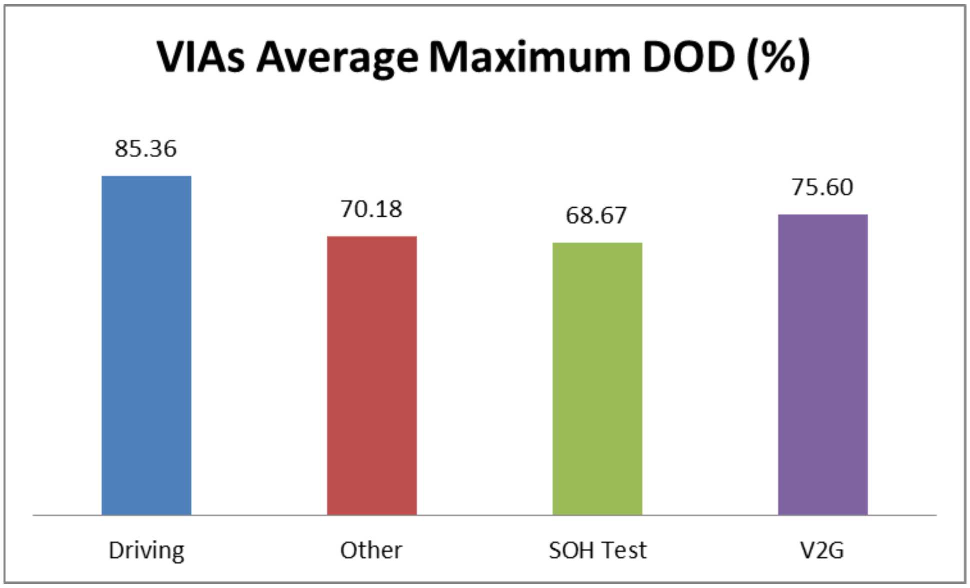


Source: Concurrent Technologies Corporation

VIA VTRUX Vans

Figure 12 shows the VIA VTRUX vans experience the largest DOD during the driving use case followed by V2G activities. The other category and SOH test were the least aggressive for these vehicles.

Figure 12: VIAs Day-by-Day Average Maximum DOD



Source: Concurrent Technologies Corporation

Report 3 – SOH Capacity Report

The SOH Capacity Report provides data captured from SOH testing, which was planned to be performed on an approximately monthly basis on each vehicle once the testing capability was developed and available. The purpose of the SOH test was to reliably and consistently determine the present energy capacity of the vehicle batteries and subsequently use these capacity measurements to quantify vehicle battery degradation over time. Each SOH test staged the vehicle batteries to a fully charged and balanced state to achieve a consistent reference point. A controlled discharge rate was conducted until a minimum pack SOC was reached.

SOH testing was dependent on software developed under the DoD demonstration. The discharge limit was dependent on the BMS SOC algorithm, which was set at 20 percent SOC. This limit was selected to ensure the non-linear portion of the battery voltage curve was not reached during testing. Therefore, consistencies were dependent on the BMS. Due to constraints during the DoD development process that delayed development of the required software, SOH tests could only be conducted from October 2016 onward.

Table 10 presents the results of the first and last SOH test events for all fleet vehicles and resultant calculated capacity degradation. Usable capacity is defined by the vendor and is limited by the BMS. The LEAFs had a usable capacity of 21.3 kWh or 89 percent of rated battery capacity, but the other vehicles had a usable capacity 80 percent of rated battery capacity (usable capacity being 81.6 kWh for the Phoenix, 43.2 for EVIs and 16.8 for the VIAs).

Technical issues resulted in several instances where vehicles were unable to complete any SOH tests and other instances where vehicles completed only a single SOH test.

Table 10: SOH Test Summary

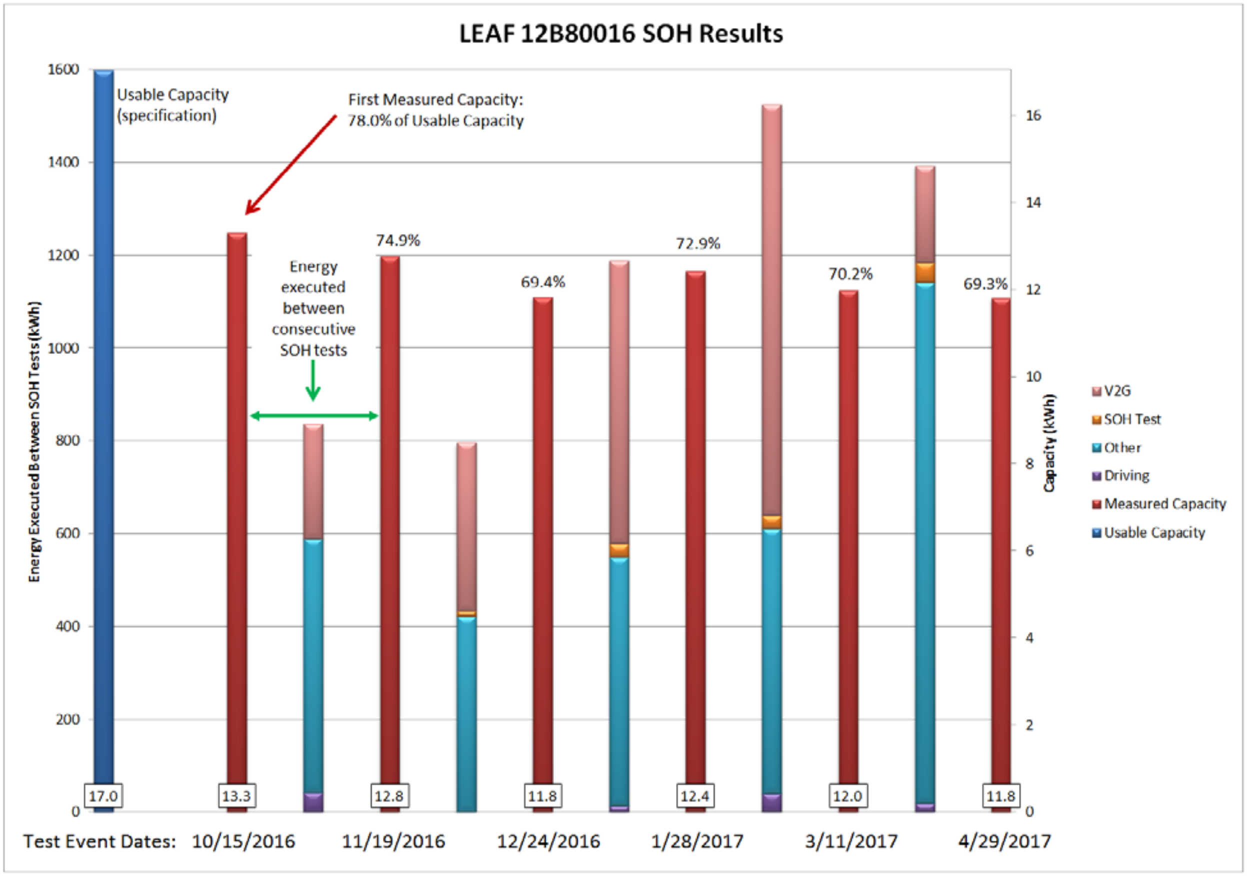
		First Test			Last Test			
Type	Vehicle	Date	Measured Cap (kWh)	% of Usable Cap	Date	Measured Cap (kWh)	% of Usable Cap	% of Usable Capacity Degradation
Nissan LEAF Sedans	12B80011	10/29/16	12.0	70.6	03/25/17	11.6	68.1	2.4
	12B80012	10/15/16	13.0	76.1	04/15/17	11.8	69.0	7.1
	12B80013	11/02/16	12.8	75.2	03/25/17	11.4	66.7	8.5
	12B80014	10/01/16	12.6	74.0	04/22/17	11.9	69.7	4.2
	12B80015	10/22/16	12.2	71.8	04/01/17	11.5	67.4	4.3
	12B80016	10/15/16	13.3	78.0	04/29/17	11.8	69.3	8.7
	12B80018	11/05/16	12.7	74.5	04/29/17	12.3	72.2	2.2
	12B80019	10/29/16	12.4	72.9	04/29/17	11.3	66.4	6.5
	12B80020	10/01/16	11.8	69.3	04/22/17	11.0	64.5	4.8
	12B80021	10/01/16	11.9	69.8	04/08/17	11.3	66.3	3.4
	12B80022	10/15/16	11.1	65.3	04/29/17	10.4	61.3	4.0
	12B80023	10/15/16	14.1	83.0	04/08/17	13.4	78.7	4.2
	12B80024	10/15/16	13.0	76.3	02/18/17	13.0	76.5	-0.2
VIA VTRUX	14Z10424	--	--	--	--	--	--	--
	14Z10425	--	--	--	--	--	--	--
	14Z10426	01/07/17	16.4	97.8	--	--	--	--
	14Z10427	03/11/17	16.2	96.4	--	--	--	--
	14Z10429	--	--	--	--	--	--	--
	14Z10430	12/17/16	16.0	95.2	04/29/17	17.8	106.0	-10.9
	14Z10431	12/17/16	16.1	96.8	04/22/17	0.5	96.9	-0.1
	14Z10432	--	--	--	--	--	--	--
	14Z10433	12/24/16	11.4	68.0	--	--	--	--
	042M778	--	--	--	--	--	--	--
	044M580	--	--	--	--	--	--	--
EVI REEV	14B80133	03/25/17	38.8	89.8	04/29/17	40.3	93.4	-3.6
	14B80134	03/11/17	41.1	95.1	04/15/17	42.4	98.1	-3.0
	14B80135	03/11/17	40.4	93.5	04/15/17	30.0	69.5	24.0
	14B80136	--	--	--	--	--	--	--
Phoenix Shuttle	14Z10434	11/26/16	79.3	97.1	12/31/16	79.1	96.9	0.3

****Note: The result of 106.0% for the last SOH test of VIA 14Z10430 was likely due to an anomalous vehicle SOC calibration instance or related to changes in battery temperature between the tests, which are known to have an impact on the capacity.**

Source: Concurrent Technologies Corporation

Figure 13 presents additional SOH test result details for an example vehicle, LEAF 12B80016. The measured battery pack capacity for each of the six SOH test events is described in both kWh and percentage of the manufacturer specified usable pack capacity. Additionally, the energy executed on this vehicle battery pack during the period between consecutive SOH test events is summarized and itemized for pertinent vehicle use categories. These tests indicate a trend that the battery capacity is degrading over time. The durations between the SOH tests show a small quantity of driving and SOH energy transfer in or out of the battery. The V2G and other categories saw a majority of the energy transfer. In a few cases, batteries show an apparent increase in capacity over time. This is likely due to the results not being corrected for temperature, which is known to have an impact on apparent capacity.

Figure 13: SOH Test Results for Example Vehicle



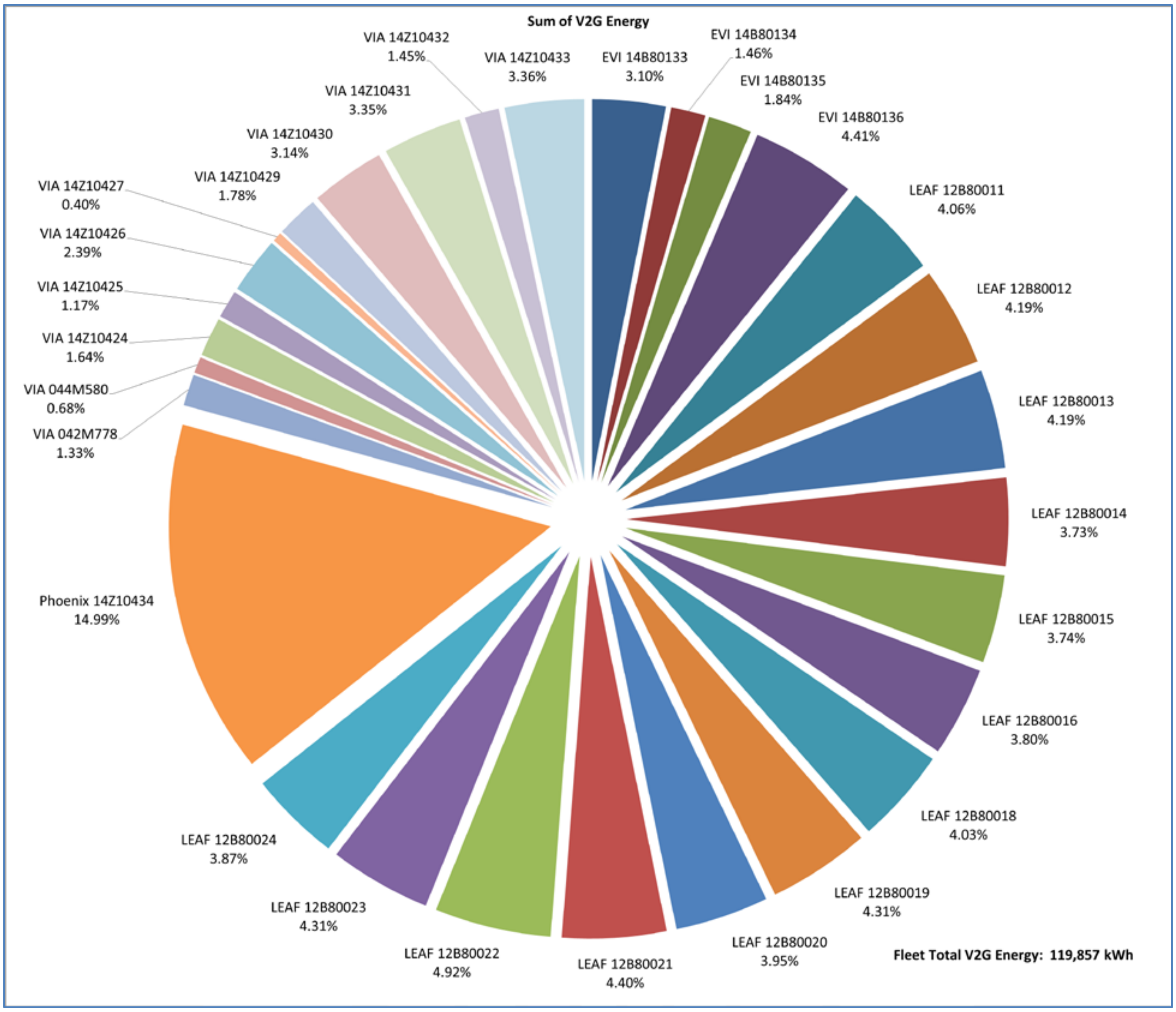
Source: Concurrent Technologies Corporation

Report 4 – Energy Report

The Energy Report provides information regarding total energy transfer for each use category per vehicle for each data source throughout the assessment period. These data permitted assessment of energy transfer for each use category over various time periods. An example of this is the categorized energy use that occurred between consecutive SOH test events, as previously discussed for Figure 13.

Two other applications of these data are found in Figure 14, which shows the fleet V2G energy use during the entire evaluation period, and Figure 15, which shows the fleet driving energy use. Figure 14 provides a summary of the V2G energy for each vehicle during the one year demonstration. On average each of the LEAFs provided 4 percent of the V2G energy, the VIA vehicles had a broader range from less than a half of a percent to more than 3 percent, the EVIs was disparate from 1.5 percent to more than 4 percent and the Phoenix provided the most at fifteen percent.

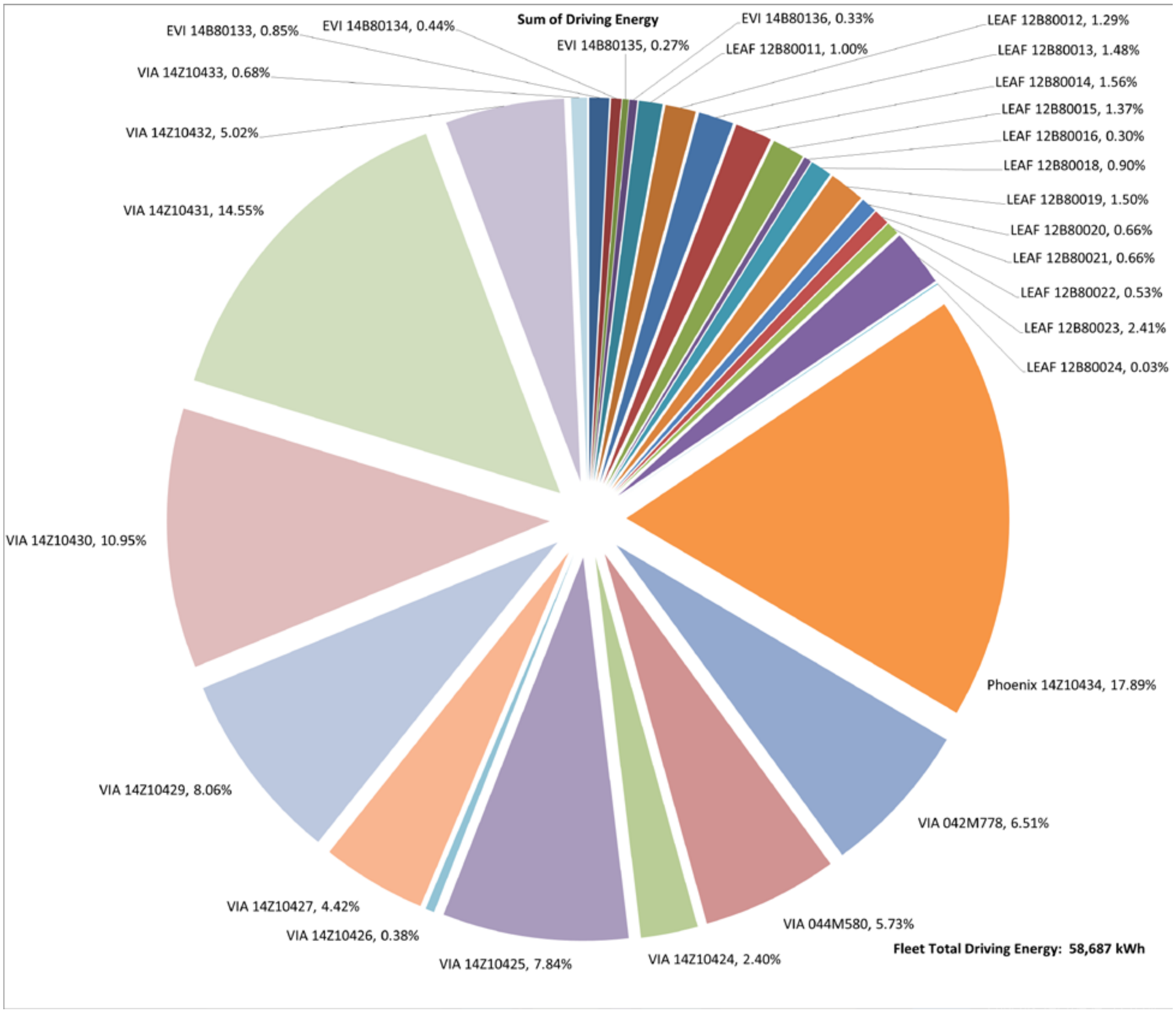
Figure 14: Fleet Total V2G Energy Use



Source: Concurrent Technologies Corporation

Figure 15 depicts driving energy per vehicle over the demonstration period. The Phoenix vehicle had the highest driving energy followed by several of the VIA vehicles followed by the LEAFs and EVIs. This aligns to the mission and use of the vehicles during the demonstration testing.

Figure 15: Fleet Total Driving Energy Use



Source: Concurrent Technologies Corporation

Results and Discussion

The U.S. DoD PEV-V2G demonstration program was the largest of its time, bi-directional non-tactical electric vehicle fleet in the world. These V2G capable PEVs and associated hardware meet rigorous military, industry, and utility standards, preparing the base to participate in the energy ancillary services market. Significant strides have been accomplished in advancing the technology, equipment, and collaborations necessary to achieve AS with aggregated PEV energy storage. The DoD program has successfully advanced bi-directional power systems technology readiness levels, developed power system infrastructure improving installation energy resiliency and assurance, and readied the base for revenue stream generation through energy ancillary services market participation. In addition, it has quantified V2G vehicle/equipment technology capabilities and identified successful performers.

The California Energy Commission participated in several aspects of this DoD program including providing technology, equipment, data collection and analysis. The data and analysis provide insights on vehicle usage and down time as well as opportunities to increase V2G activities.

The level of AS market participation during this demonstration was low in comparison to a fully implemented, wide-scale V2G program. In such a program, vehicles would need to be available for participation in the V2G storage market at any time outside of typical vehicle driving hours, which would be greater than 12 hours per day on weekdays and possibly 24 hours a day during weekends. In such an environment, the total energy cycling resulting from V2G would undoubtedly be higher than that observed during these field demonstration tests.

SOH Testing Conclusions

SOH testing was instituted to measure battery capacity in an effort to quantify battery degradation. The general trend for most vehicles tested showed a slightly lower energy storage capacity as a result of battery usage. However, the results were not corrected for temperature effects, and the SOH tests were only conducted over six-month time frame. This combination of factors may be the primary cause for an apparent improvement in battery capacity after the usage defined for several of the vehicles.

Additionally, the SOH testing was limited by vehicle battery management systems, which by design did not allow vehicle batteries to be fully discharged. Therefore, the SOH tests were not allowed to reach the non-linear portion of the battery voltage curve found only at extremely low states of charge, making it difficult to impossible to gauge small amounts of degradation of these battery packs.

Technical Challenges

The DoD PEV-V2G Demonstration was a technically challenging pilot project that made use of prototype or limited run PEVs and PHEVs, as well as EVSEs custom-designed for the demonstration. This resulted in the vehicles being unable to participate in the V2G market or even on driving missions for long periods of time during the demonstration. Overall, only the Nissan LEAF sedans and the Phoenix shuttle had the performance stability to be considered typical for a fully commercialized V2G fleet; however, these vehicles also suffered limited periods of unavailability. Consequently, large-scale V2G operations will require careful contingency planning for the assets use across a given timeframe.

CHAPTER 3:
Laboratory Research, Testing and Analysis

CTC conducted independent laboratory testing on PEV battery system test articles to evaluate the effects of V2G operations. To accomplish this goal, two identical battery systems were procured from two vendors—in each pair, one battery pack (Control Pack) was used as a baseline for simulated driving missions and the other (V2G Pack) simulated both driving missions and V2G operations. Driving and V2G activities (frequency regulation) were simulated in a controlled manner over time to gain a better understanding of potential V2G impacts on battery life.

The following sections discuss the technical approach of the laboratory testing effort, including:

- An overview of the laboratory testing infrastructure, including the PEV battery test articles, test facility and test system controller.
- An overview of the test sequences conducted during laboratory testing, including simulated driving scenarios, simulated V2G activities and discharge cycles used to quantify battery health.
- An examination of factors leading to degradation and the differences that each battery pack experienced during laboratory testing as the result of the driving and V2G profiles.
- The analysis conducted on the test data to quantify V2G degradation, in addition to technical issues that influenced the results.

Laboratory Testing Infrastructure

The following sections detail the battery test articles, laboratory testing facility and test system controller used to facilitate the laboratory testing effort.

Battery Test Articles

Two types of lithium-ion battery systems were procured as test materials for this effort—1) the battery system manufactured by VIA Motors (VIA) and used in VIA's PHEV VTRUX vans and 2) a set of battery modules from Valence Technologies (Valence) that were assembled into a scaled version of the battery packs used in PEVs. Table 11 summarizes these test materials, describing the battery rated capacity and battery chemistry.

Table 11: Battery Systems Procured

Vendor/ manufacturer	Number of systems procured	KWh capacity per battery pack	Battery chemistry
VIA	2	21.1	$LiFePO_4$
Valence	2*	24.7	$LiFeMgPO_4$

***Total of 28 battery modules, integrated into two battery packs of 14 modules each.**

Source: Concurrent Technologies Corporation

The VIA battery systems were not put into full testing because performance issues prevented execution of the testing profiles. Since test data for the VIA battery systems could not be collected, the data and analysis of this chapter is focused on the testing performed on the Valence battery packs.

Laboratory Testing Facility

CTC conducted testing at the Center for Sustainable Energy (CSE) Second Life Battery Research test bed, located in the University of California San Diego (UCSD) Hopkins parking garage. This facility, connected to UCSD's microgrid and co-located with a 300-kW photovoltaic array, was capable of simultaneously testing up to four full-size PEV battery packs for a total of 120 kW peak power. Independent control, monitoring and data acquisition were integrated with the existing facility.

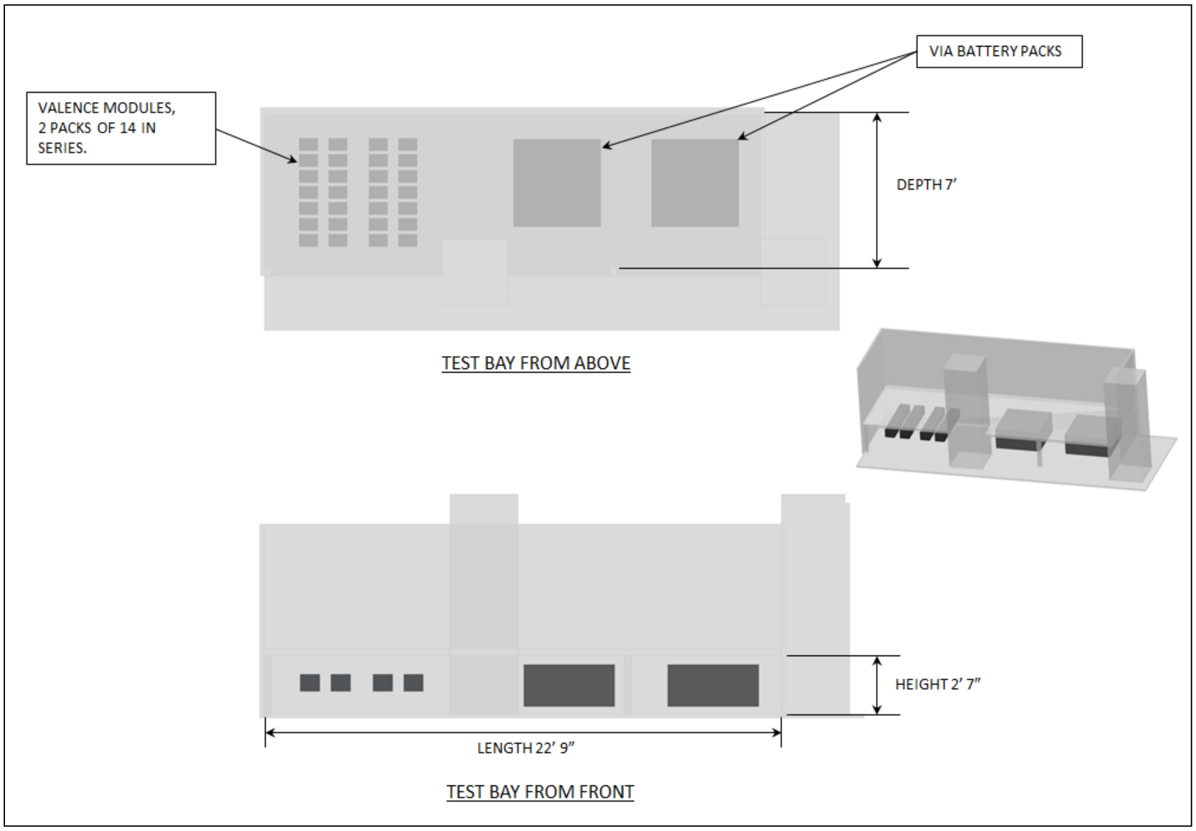
The testing facility included two AeroVironment ABC-150 bi-directional grid-tied power inverters, used for power transformation and flow control between the electric grid and the electric vehicle battery packs. Each ABC-150 inverter was capable of two independent channels, each of which could be used to charge or discharge a battery. As delivered by the manufacturer, each ABC-150 inverter was capable of providing a total charge or discharge capability of 125 kW; however, as implemented at CSE, each ABC-150 inverter was limited to a total discharge capability of 60 kW. This allowed for a maximum charge or discharge capability of 120 kW for both ABC-150 inverters combined.

The CSE test bed is pictured in Figure 16, and the test bay layout is shown in Figure 17.

Figure 16: CSE Test Bed

Source: Concurrent Technologies Corporation

Figure 17: Test Bay Layout



Source: Concurrent Technologies Corporation

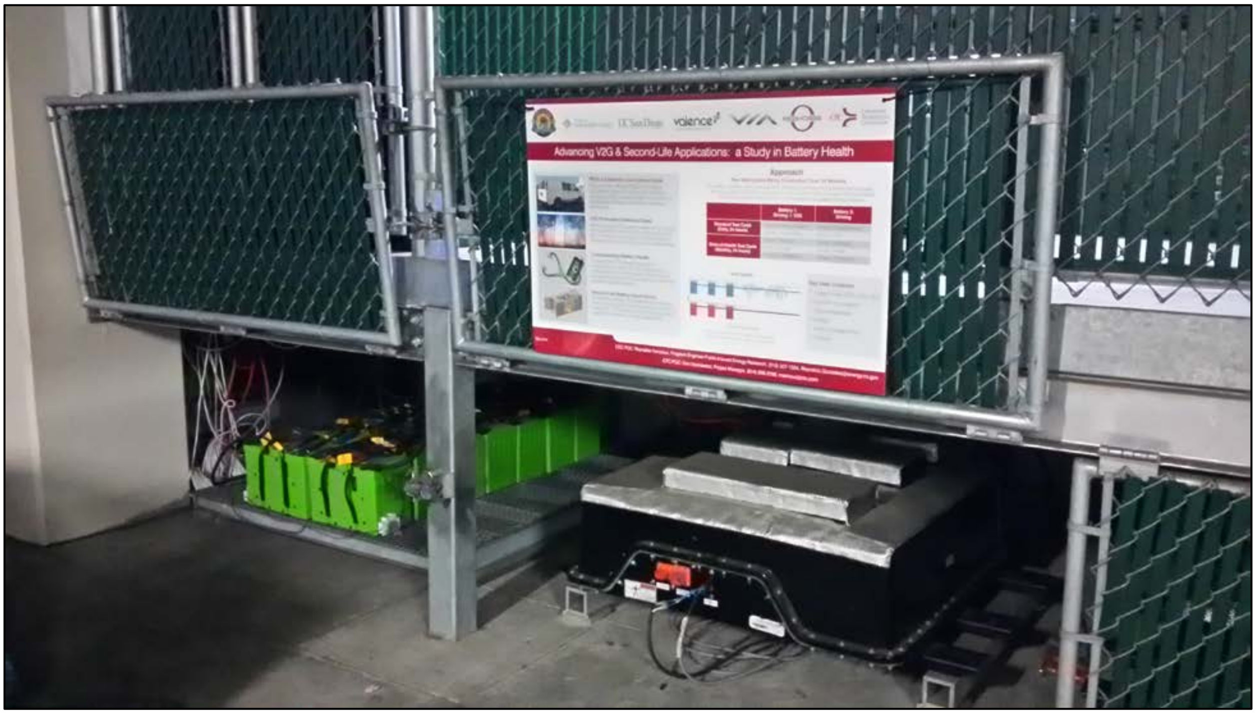
Figure 18 shows the test articles in the UCSD test bay. A Valence battery is pictured on the left, and a VIA battery is on the right.

Test System Controller

Efficient and effective execution of the planned laboratory testing required an automated control and monitoring system to manage unattended operations of the test system. CTC implemented a test system controller platform to satisfy this requirement. Core capabilities of the test system controller included:

- Autonomous execution of power flow profiles on the laboratory PEV battery systems.
- Monitoring of and communication with each battery system's battery management system (BMS).
- Power transformation and flow control between the electric grid and each battery system.
- Data acquisition and logging of resultant performance measurements.
- Report generation.
- Remote system management, monitoring and data retrieval.

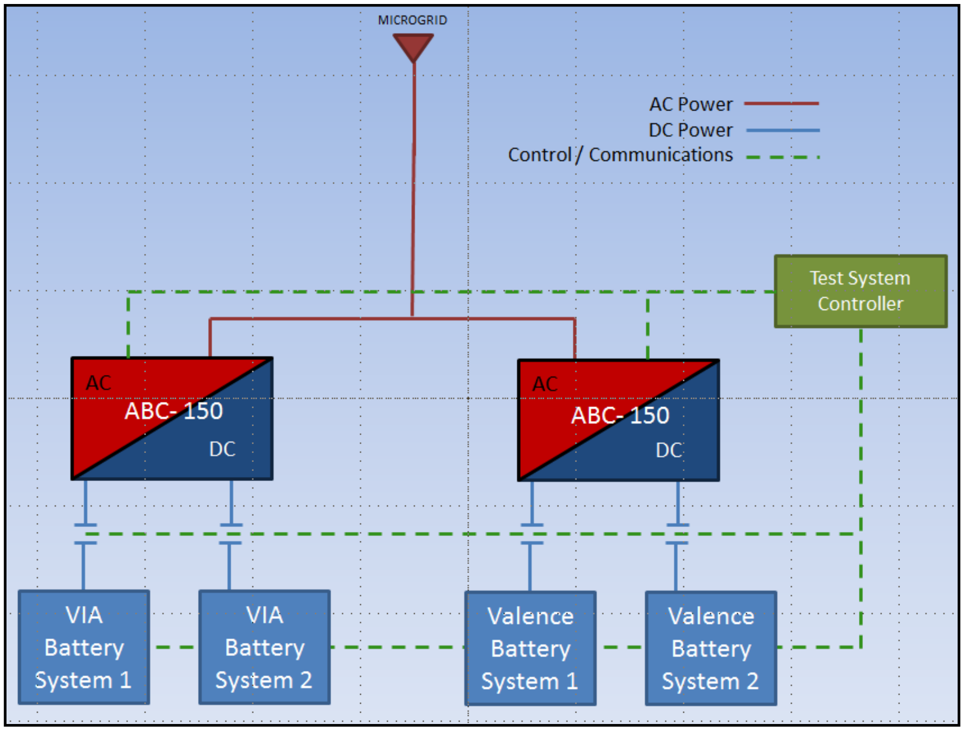
Figure 18: PEV Battery Test Articles



Source: Concurrent Technologies Corporation

The design concept for the laboratory test bed is shown in Figure 19. The test system controller communicated with the two AeroVironment ABC-150 power processing systems and the four subject battery systems to control power flow and monitor operating conditions. Each ABC-150 power processing system served as a controllable bi-directional AC/DC converter and facilitated power transfer between the DC battery systems and the AC electrical grid interconnect. This enabled charging and discharging of the battery systems. The test system controller also controlled DC contactors to manage connectivity between the battery systems and the ABC-150 power processing systems.

Figure 19: Test Bed Design Concept



Source: Concurrent Technologies Corporation

Test Plan

Table 12 summarizes the planned tests. Each battery pack underwent several hundred tests, including standard test cycles, state-of-health (SOH) tests and nameplate capacity comparison (NCC) tests. These tests are further discussed in the following sections.

Table 12: Test Plan

	Control Pack	V2G Pack
Standard Test Cycle (Daily, 24 hours)*	12 hours – Driving Scenario	
	12 hours – Charge / Float	12 hours – V2G Scenario
State-of-Health Test Cycle (Monthly, 24 hours)	6 hours – Discharge	
	6 hours – Charge	
	12 hours – Cell Balance	
Nameplate Capacity Comparison Test Cycle	9 hours – Charge / Float Charge	
	6 hours – Discharge	
	9 hours – Idle / Charge / Cell Balance / Float Charge	

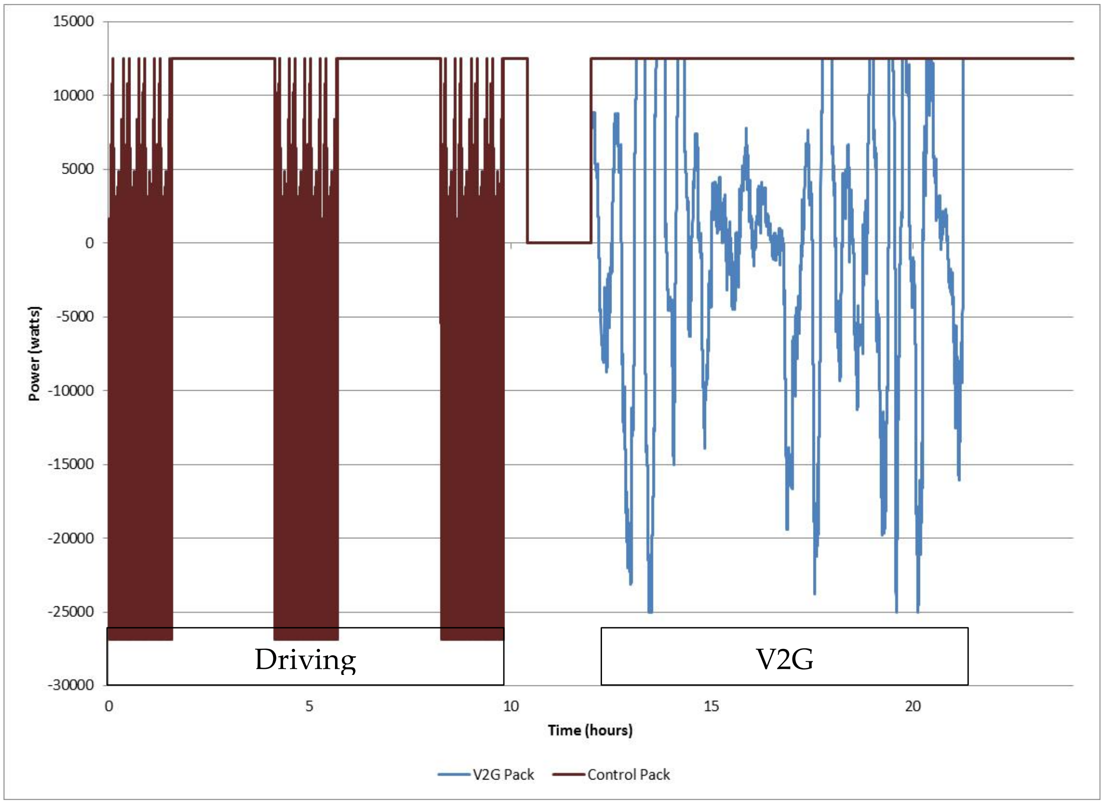
*** The intent was to run the standard test cycle on a daily basis, however as noted in the Technical Issues section of the Data Analysis, this was not always possible.**

Source: Concurrent Technologies Corporation

Standard Test Cycle

The standard test cycle was 24 hours in duration and subjected both battery packs to simulated driving missions in the first 12 hours and subjected the V2G Pack to simulated V2G operations in the next 12 hours while the Control Pack completed its charge cycle and then remained a float charge. This standard test cycle was an aggressive test profile developed to achieve accelerated degradation while adhering to manufacturer battery specifications (e.g., peak and maximum continuous discharge limits). Figure 20 shows a graphical representation of the standard test cycle, including driving and V2G operations.

Figure 20: Standard Test Cycle



Source: Concurrent Technologies Corporation

Table 13 provides details on each drive and V2G segment. The total duration for driving is 4.68 hours while the V2G segment is 9.25 hours. This does not include the time allotted for charging after each of these segments. Additionally, the energy in and out values in Table 3 are only based on the segment and does not include the energy to charge the battery after the respective segment. It is worthy to note some details about these two cycles. The driving segments require a total of approximately 57 kWh of energy to pass through (i.e., sum of energy out and energy in) the battery in 4.68 hours while the V2G segment requires approximately 66 kWh of energy to pass through the battery in 9.25 hours. The ratios of total energy (in plus out) to cycle time are 12.08 and 7.14 kWh/h for the driving and V2G segments, respectfully. In addition, the V2G segment is referred to as energy neutral, i.e., the energy out is approximately equal to the energy in.

Table 13: Standard Test Cycle Duration and Energy Usage

Parameter	Drive Cycle 1	Drive Cycle 2	Drive Cycle 3	Driving (Total)	V2G Cycle
Duration (Hours)	1.56	1.56	1.56	4.68	9.25
Energy – Out (kWh)	18.63	18.63	18.63	55.89	36.06
Energy – In (kWh)	0.22	0.22	0.22	0.66	30.03

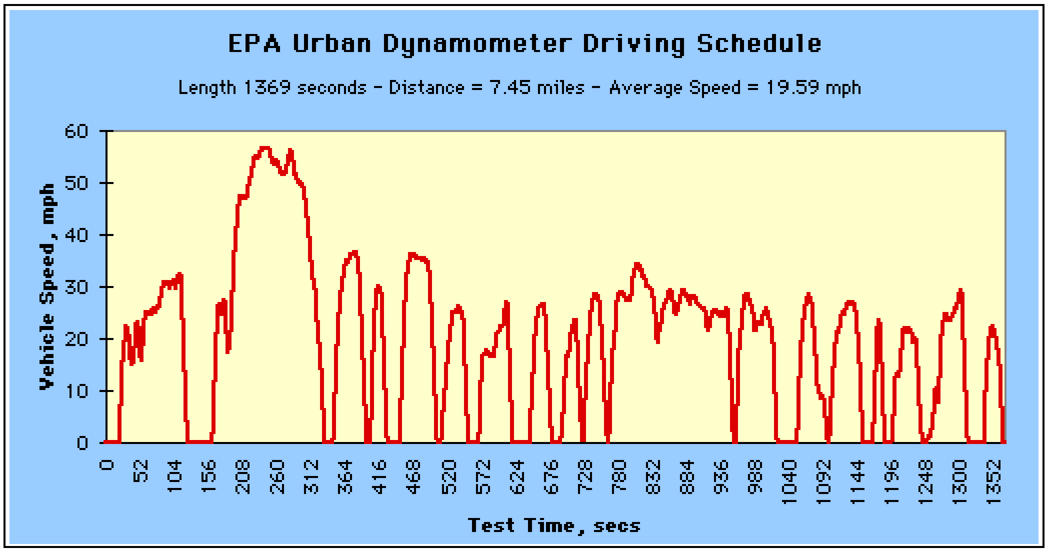
Energy and time to charge the battery after each drive cycle and V2G cycle is not included in this table. The energy in values for the driving cycles result from simulated regenerative braking.

Source: Concurrent Technologies Corporation

Driving Scenario

The driving scenario executed the Urban Dynamometer Driving Schedule (UDDS) using the test system controller and the ABC-150 bi-directional grid-tied power inverters. Depicted in Figure 21, the UDDS sequence simulates an urban route of 7.45 miles (12.0 km) with frequent stops; this driving schedule requires 22.8 minutes to complete. The maximum speed is 56.7 mph (91.2 kph) and the average speed is 19.6 mph (31.5 kph).[1]

Figure 21: UDDS Driving Cycle[2]



Source: Concurrent Technologies Corporation

The laboratory driving scenario test is pictured in Figure 22. The UDDS profile was slightly modified (clipped) to adhere to battery manufacturer threshold specifications and repeated four times to fulfill one drive cycle. Each drive cycle, which included four consecutive modified

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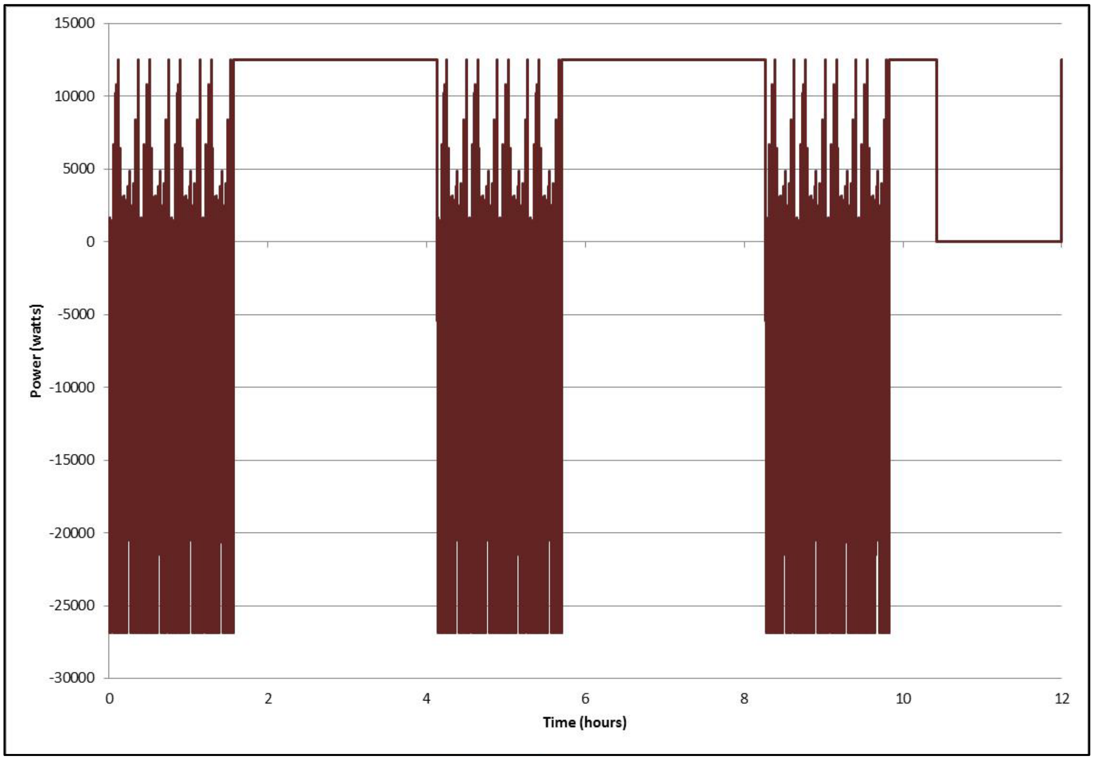
[1] http://dieselnet.com/standards/cycles/ftp72.php

[2] http://www.epa.gov/oms/standards/light-duty/udds.htm

UDDS profiles, simulated an urban route of 29.8 miles. Therefore, each daily standard test cycle simulated an urban route of 89.4 miles within 4.56 hours, not including charge time. The 12-hour driving scenario consisted of the following steps:

1. Assume each battery pack is charged to the maximum state-of-charge (SOC) threshold (100 percent SOC) and cell balanced
2. Drive Cycle 1
    a. Execute the modified UDDS sequence 4 times
    b. Fully charge the pack and perform cell balancing
3. Drive Cycle 2
    a. Repeat steps 2a and 2b
4. Drive Cycle 3
    a. Repeat step 2a
    b. Charge the pack to 55 percent SOC and remain idle until the end of the first 12-hour period in preparation for the second 12-hour period.

Figure 22: Valence Driving Scenario



Source: Concurrent Technologies Corporation

V2G Scenario

The LAAFB PEV-V2G demonstration participated in the CAISO frequency regulation AS market where the batteries were used to correct short-term changes in the 60-hertz electric grid alternating current (AC) frequency. The CAISO AS frequency regulation automated generation control (AGC) signal indicated the power levels at 4-second intervals needed to satisfy the PEV-V2G system AS award received in response to a day-ahead bid.

The laboratory testing V2G scenario simulated a V2G participation period where the vehicle was stationary, connected to a charging station and participating as a V2G resource. The source of the AGC signal used in laboratory testing was a duty cycle established by the CSE and KnGrid and used in testing as detailed in the report "Short Term Duty Cycle Test Report, Regulation Energy Management (REM) Duty Cycle, Battery Pack: A123 #2, Channel 3." This duty cycle was based on a 7-day CAISO AGC signal from July 1 to July 7, 2010.

The V2G scenario executed on the V2G Pack is pictured in Figure 23. The 12-hour V2G scenario for the V2G Pack consisted of the following steps.

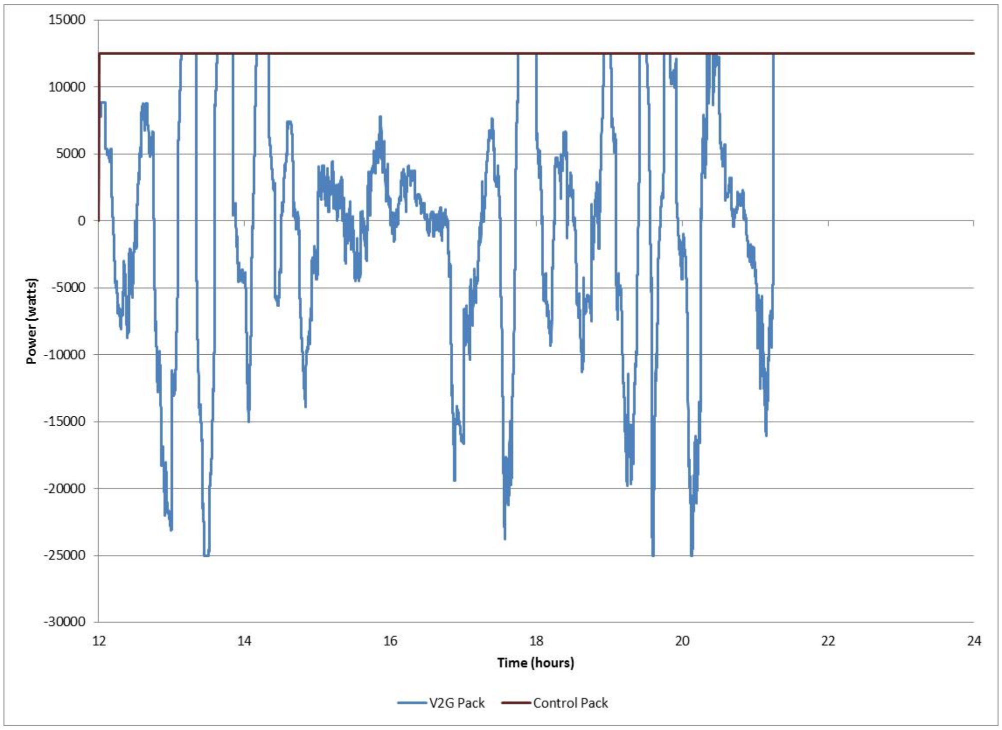
1. Assume each battery pack is charged to 55 percent SOC in preparation for V2G participation.
2. Execute dynamic charging and discharging at the command of the AGC signal for 9.25 hours.
3. Fully charge the pack and perform cell balancing.

In the same 12-hour time period, the 12-hour scenario for the Control Pack consisted of the following steps.

1. Fully charge the pack and perform cell balancing.
2. Float charge the pack to complete the 12-hour period.

It should be noted that the power command is 12 kW; however, the BMS controlled actual power to the battery pack based on its SOC.

Figure 23: Valence V2G 12-Hour Power Command



Source: Concurrent Technologies Corporation

State-of-Health (SOH) Test Cycle

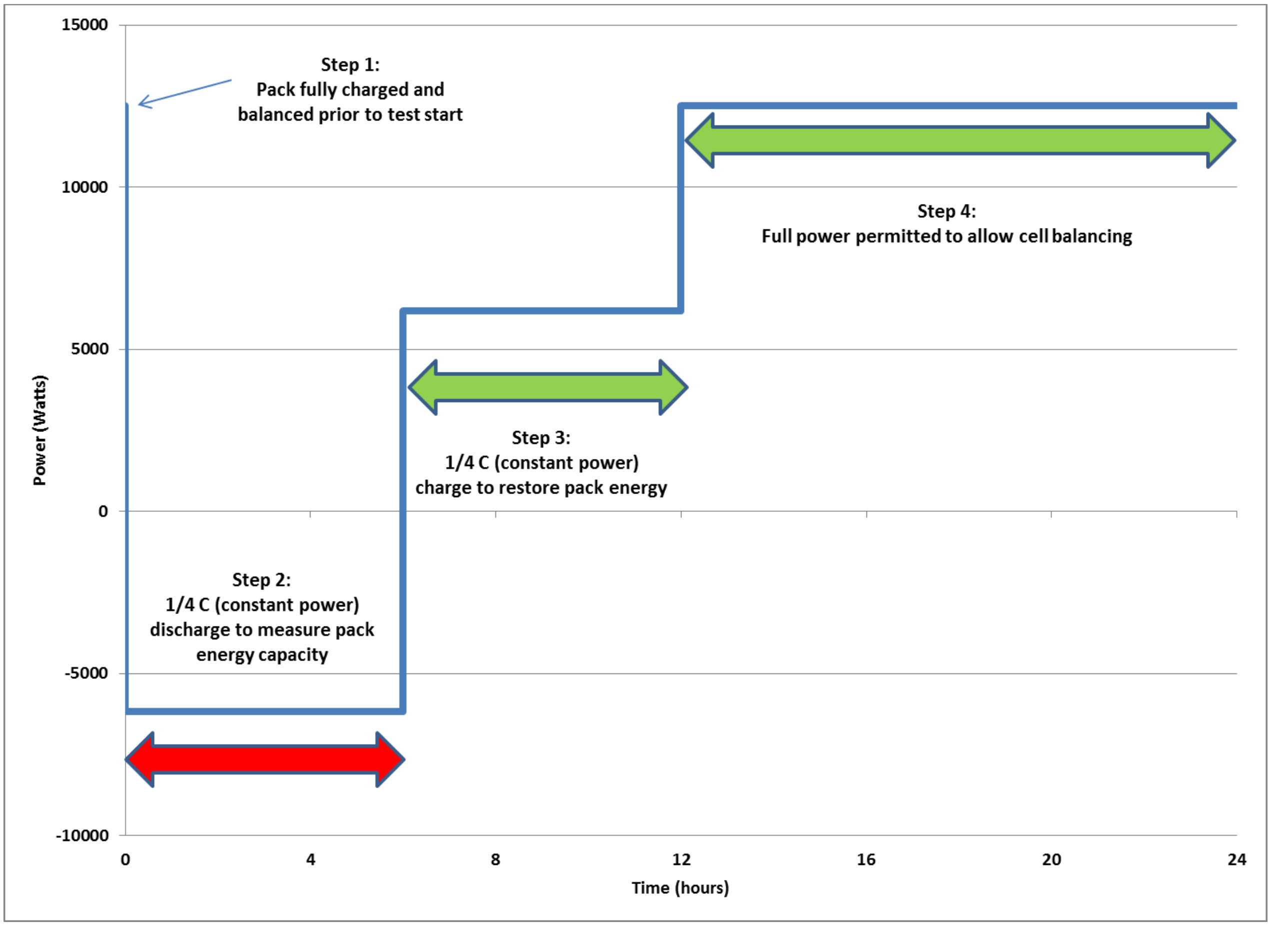
Battery performance traits were scientifically assessed to quantify potential performance degradation resulting from adding daily V2G duty cycles to the normal daily PEV driving duty cycles. This assessment was accomplished through the execution of a monthly SOH test cycle that permitted collection of battery SOH data during the laboratory-testing period. This cycle primarily discharged each battery to a minimum threshold while measuring the amount of energy removed from the batteries. This process quantified pack energy capacity.

The SOH test cycle is pictured in Figure 24. The 24-hour cycle consisted of the following steps for each battery.

1. Prior to the test, each battery pack is charged to the maximum SOC threshold (100 percent SOC) and cell balanced.
2. Discharge from the maximum threshold at the manufacturer's recommended rate to the discharge termination state as identified by battery manufacturer cell characteristics, while measuring the amount of energy removed from the battery.
3. Charge from the minimum threshold at the manufacturer's recommended charge rate to the maximum voltage as identified by battery manufacturer cell characteristics.
4. Make full charger power available to the battery pack to permit cell balancing.

This process quantified battery capacity and provided a means of assessing degradation and projecting battery performance. Comparing energy removed from each battery allowed degradation to be characterized over time throughout the test period. While the SOH test cycle was intended to be executed monthly, it was occasionally executed more frequently for improved data collection (e.g., once per week versus once per month).

Figure 24: State-of-Health Test Cycle

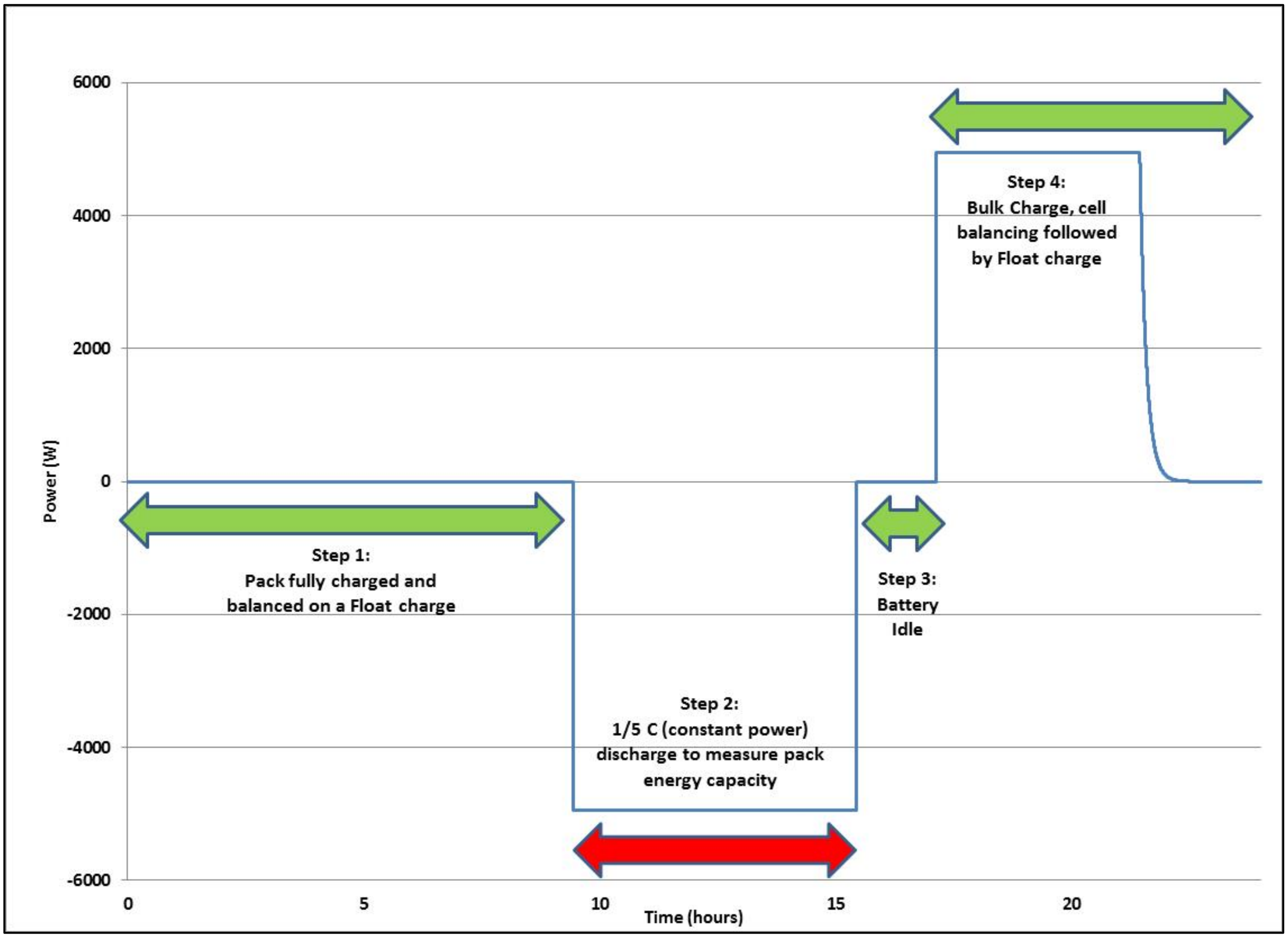


Source: Concurrent Technologies Corporation

Nameplate Capacity Comparison Test Cycle

Pictured in Figure 25, the NCC test has a 24-hour test cycle that allowed measurement of pack energy capacity directly comparable to the manufacturer “nameplate” (rated) capacity (24,724 watt-hours [Wh] or 138 amp-hours [Ah]). The battery capacity was calculated based on 14 battery modules rated at 1,766 Wh each. Each battery pack was fully charged and balanced followed by a float charge for up to nine hours. Each pack was discharged to a low pack voltage limit of 140 volts or 0 percent SOC. The energy discharge capacity was measured and compared to the nameplate specification based on a 1/5 C rate per Valence specification. The pack was then recharged, and this energy was used to calculate battery energy efficiency.

Figure 25: Nameplate Capacity Comparison Test Cycle



Source: Concurrent Technologies Corporation

Driving and V2G Cycle Comparison

To truly understand potential degradation resulting from V2G participation, one must investigate and understand the factors leading to battery degradation and the aggressiveness of each respective profile. Based on the approved test plan, both packs performed identical drive cycles simultaneously; the V2G Pack also completed the V2G cycle. Several differences in pack operation ultimately led to additional capacity fade (reduction) within the V2G Pack. This section discusses the factors that led to degradation and differences that each Valence battery pack experienced during this testing as the result of the driving and V2G profiles. As mentioned earlier, the VIA battery systems were not put into full testing because performance issues prevented execution of the testing profiles.

Battery degradation results in capacity loss and power fade due to chemical and mechanical degradation mechanisms.

- Chemical degradation is manifested in several factors, including 1) the loss of the ability to recycle lithium resulting from lithium-consuming solid electrolyte interphase (SEI) layer growth and side reactions, 2) increased interfacial resistance due to the catalytic growth of the SEI layer on the graphite anode and 3) increased electrolyte resistance.

- Mechanical degradation is caused by battery stresses and strains in the electrodes, which increases with battery calendar aging and aggressive battery usage.

The degradation of lithium-ion cells depends on the number of cycles completed as well as the operational conditions consisting of temperature, charge/discharge rate, DOD and average SOC. The following sections summarize factors that contribute to degradation and how each battery pack was impacted by these factors.

Calendar Aging

The aging processes leading to battery degradation with the exception of battery usage (cycles) is referred to as calendar aging. The two primary driving parameters are temperature and time. The predominant mechanism of calendar aging is the evolution of passivation layers at the electrode–electrolyte interfaces. The formation, growth or reconstruction of passivation layers consume the recyclability of lithium as a result of electrolyte decomposition.[3]

Both battery packs were procured at the same time and therefore are assumed to have the same calendar aging effect due to time. The battery manufacturer indicated the expected capacity fade is one to two percent per year. However, the temperatures of the two test packs were not consistent due to the increased power demands required of the V2G cycle. This will be further discussed in the data analysis section.

Cycles

A battery cycle is commonly understood as the complete discharge of a fully charged battery with a subsequent recharge. Battery manufacturers provide cycle life projections as the number of cycles at a given C-Rate (C), DOD and temperature until battery capacity drops to 80 percent of the name plate capacity. This is difficult to correlate with actual usage because most cycles do not follow this identical pattern and the ambient temperature during operation of transportation batteries is rarely constant. Batteries are usually operated under partial discharges of varying depth before complete recharging. Since the amount of degradation is heavily dependent upon the DOD, and due to the irregular DOD and ambient temperatures actual batteries experience, the battery manufacturers' life cycle predictions are best used to judge relative life among various battery options.

During the laboratory testing, battery packs experienced the same number of driving cycles at nearly 1,500 cycles, while the V2G Pack experienced an additional 464 V2G cycles.

Use (Total Energy)

Another factor in battery degradation is usage or total energy. This is the total energy (in watt-hours) passing through (i.e., removed or added) to the battery. As a battery is charged and

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[3] Keil, Peter, Simon F. Schuster, Jorn Wilhelm, Julian Travi, Andreas Hauser, Ralph C. Karl and Andreas Jossen, "Calendar Aging of Lithium-Ion Batteries," Journal of The Electrochemical Society, 163, pp. A1872–A1880, July 2016.

discharged, electrode materials swell and contract. This repetitive cycling weakens the electrode structure, reducing its adhesion to the current collector.

This degradation factor is obvious for the V2G Pack with an absolute total energy value of 59 percent more than the Control Pack. This additional use was primarily due to the V2G profile and will be further discussed in the data analysis discussion.

Depth of Discharge (DOD)

The DOD is a measure in percentage of the amount of energy removed from a battery relative to its current full-charge capacity. By definition, its value plus the SOC must total 100 percent. For example, if the SOC is 80 percent, the DOD is 20 percent. Batteries experience more degradation and shorter life when experiencing higher DOD. In some cases, reducing DOD from 100 percent to 80 percent can double the cycle life of a battery.[4]

As shown in Table 14, the standard test profile was developed to achieve a discharge of 74 percent of the battery nameplate capacity during each drive cycle with the understanding that, as the battery packs degraded, the actual DOD would increase. Similarly, the V2G profile was developed to achieve a discharge of 71 percent of the battery nameplate capacity.

Table 14: Theoretical DOD

Theoretical based on test profile	V2G Pack Maximum DOD (%)	Control Pack Maximum DOD (%)
Drive Cycle 1	74	74
Drive Cycle 2	74	74
Drive Cycle 3	74	74
V2G Cycle	71	N/A

Source: Concurrent Technologies Corporation

The DOD for the V2G Pack was on average lower than the Control Pack. This was primarily due to the additional usage seen by the V2G Pack and the deeper usage of battery capacity to achieve the standard profile.

Temperature

Temperature has a strong impact on the degradation of lithium-ion batteries. Most battery corrosion occurs during charge/discharge cycles. This corrosion increases at higher temperatures. The best cycle life can be obtained at moderate temperatures, because low temperatures decrease cycle life due to intensified lithium plating, and high temperatures reduce battery life due to Arrhenius-driven aging reactions.

Based on the continual use of the V2G Pack, it exhibited a higher temperature than the Control Pack.

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[4] https://www.valence.com/why-valence/long-lifecycle/

C-Rates

Battery charge and discharge current is expressed as a C-Rate to normalize against battery capacity typically listed in amp-hours. However, the current used as the basis for C-Rate often varies among battery models. A C-Rate is a measure of the rate at which a battery is charged/discharged relative to its rated amp-hour capacity. A 1C rate means that the discharge current will discharge the entire battery capacity in 1 hour. For a battery with a capacity of 100 amp-hours, this equates to a discharge current of 100 amps. A 5C rate for this battery would be 500 amps, and a C/2 rate would be 50 amps. The higher the C-Rate, the more the internal cells will corrode due to self-heating. The rate of corrosion will accelerate as the internal resistance of the battery increases due to aging (the higher resistance creates internal heat in the cell).

The data analysis discussion provides greater detail on the C-Rates required to meet the power demand for both the driving and V2G scenarios. Because the profiles were commanded as a power level, the C-Rates were not directly controlled. This would have been limited by the BMS to a maximum level based on the SOC of the battery pack. As discussed in the Data Analysis Section, the C-Rates required during the drive cycle were more aggressive than the V2G cycle.

Float Charge

Float charge refers to a constant-voltage, low-current charge that counteracts the battery's self-discharge effects. This constant voltage is maintained after the battery is fully charged to ensure the battery remains fully charged. Following manufacturers' recommendations for charging should not yield a significant degradation; however, there have been several studies suggesting maintaining SOC above 20 percent and below 85 increases battery life.

By the nature of the test plan, the Control Pack spent 40 percent of the calendar time on a float charge or 100 percent SOC in comparison to the V2G Pack, which experienced 15 percent of calendar time on a float charge. Attempts to quantify this effect were not fruitful as the impact of float time could not be mathematically separated from calendar time.

Data Analysis

The following sections detail the analysis conducted on Valence test data to quantify V2G degradation. Test data were first collected in February 2015after the development and testing of the control, monitoring and data acquisition system. The first SOH test was completed on April 27, 2015 with the first complete standard completed on April 28, 2015. Each of the 778 data files generated over the test period was classified into the groups identified in Table 15.

Table 15: Test File Classification

Profile Type	Description
Standard	Normal driving + V2G
SOH	State-of-health
NCC	Nameplate Capacity Comparison
Charge	Charge and cell balance
Issue	Incomplete tests

Battery use data was collected from all of the classified profile types. Throughout the test period, occasions arose where some tests were halted. A summary of Valence issues is included in the Technical Issues Section to help explain gaps in data that appear in the analysis. To minimize any spurious effects associated with extreme data values, which most often were identified as an issue, an entire test file was eliminated from the full data collection set when errors were noted or when unusual data values were present. For example, the latter category included data entries having calculated energy efficiencies greater than 100 percent. In total, 84 standard data entries were eliminated from the detailed statistical analysis; 73 were due to error conditions and the remainder due to incomplete data. Of the 23 data entries for SOH, one was eliminated from detailed statistical analysis because of suspicious test results.

The analysis consisted of investigating the combined usage of all activity on a battery pack to maintain a cumulative record of any parameter. In other cases, such as the standard profile, data were used to obtain insight from a side-by-side comparison of the V2G and Control Packs. The SOH data sets were focused on obtaining a measure of battery capacity fade over time. In the remaining portions of this document, the baseline is referred to as the initial condition of the perspective pack at the start of testing. However, it is important to note that the standard test cycle data and SOH data sets represent different parameters. Therefore, baseline values for the standard test cycle data set do not match those of the SOH data set.

Differences between the V2G Pack and the Control Pack were quantified based upon time or total energy through the perspective battery pack. These differences were used to quantify the impact of the V2G cycle on battery degradation, which is simultaneously caused by both calendar aging and cycle aging. Separation of these calendar aging and cycle aging effects was attempted using more than one approach; however, the resulting rate effects differed by over 50 percent between these methods. Therefore, none of the separation methods were deemed worthy of inclusion in this report since one or more significant assumptions in the methods were likely not valid. Without the ability to mathematically separate the individual effects of calendar and cycle aging, no statistical assessment could be made to distinguish between the time-based and total-energy-based parameters.

Two different approaches were used to analyze the data—single and multiple parameter curve fits.

- Easier to visualize and understand, plots of single factors on measures of battery performance were produced to quickly gain an understanding of battery pack performance. These plots were also useful to visually determine when additional factors impacted measurement variability and to qualitatively assess orthogonality among the factors and responses. The battery community has clearly demonstrated that battery performance is dependent upon several variables including battery temperature, rate of charge/discharge, calendar and cycle aging, and total energy.
- To complement the single-parameter assessments, multi-variable statistical analyses were completed. The commercial statistical analysis package JMP® from SAS was used to develop empirical models to define battery performance while accounting for effects of multiple factors, most notably pack temperature and either time or total energy. In

this way, the variability associated with a single-factor analysis could be reduced and improved comparisons between the two battery packs obtained.

Judgment in these cases was needed to select the final form for any given empirical equation. The authors balanced several factors when settling on the set of factors to include for any statistical analysis. The following guidelines were used in determining the final set of factors:

- Choose highly statistical significance factors
    - Those factors with large student t values
- Strong overall fit of the empirical model to the data
    - As indicated by R^2 values close to 1.0
- Simple, yet robust equation
    - Minimal number of factors (i.e., independent variables)
    - Minimal effects beyond linear relationships
- Similar mathematical form for V2G Pack and Control Pack.

Temperature Comparisons

Since the test data were collected over a period of over 600 days, with day 1 assumed to occur on April 27, 2015 (first SOH test), the ambient temperature[5] varied significantly over time as noted in Figure 26. Although not shown here, other temperatures showed the same general shape as ambient temperature. The curve shows a seasonal effect with late summer temperature peaks and winter temperature lows. This M-shaped curvature[6] was often observed in the single-variable results as undulations around the best-fit line to the data. Figure 27 shows a typical example of this effect. The energy efficiency of both battery packs increased with temperature; therefore, temperature effects were included in the multi-factor model of energy efficiency, as discussed below. When this undulating behavior was observed, the most appropriate temperature measure was included in the multi-variable analysis. Due to the challenges in graphically showing the fit of the multi-factor empirical equation to the measurements, simple statistical results and their interpretation are provided.

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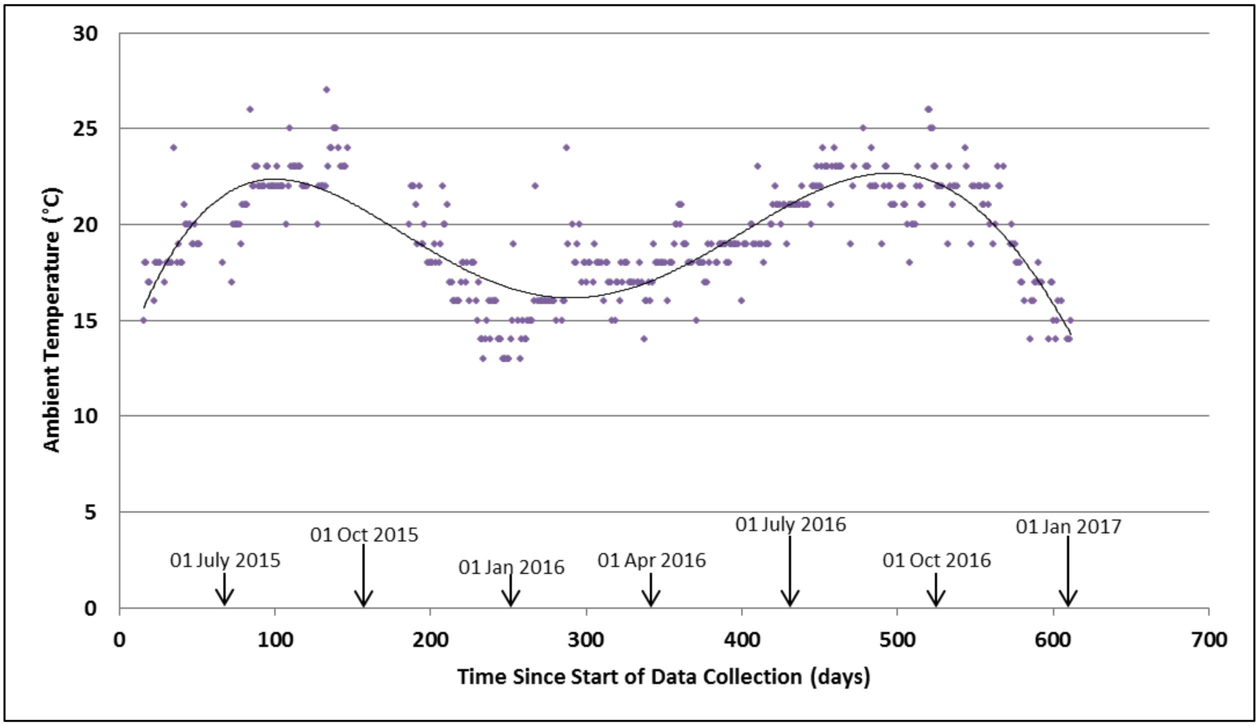
[5] The original daily ambient temperature measurements were rejected since they varied by less than 1.5 °C over the entire test period. Given the location of the test setup (an isolated, interior wall of a parking garage), use of data from common historical weather databases was deemed inappropriate. The best measure of daily ambient temperature was the minimum temperature of the Control Pack just before the start of the first drive cycle when the battery pack was concluding a long state of rest. Therefore, these values were used for daily ambient temperature. Battery operating temperatures were assumed to be accurate; generally, mean battery pack temperatures were used for analyses.

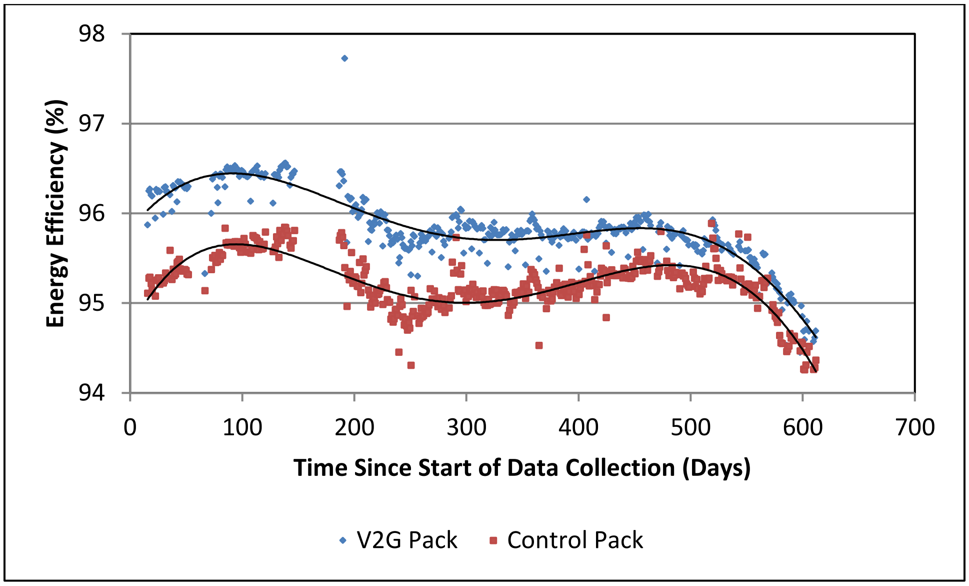
[6] This curve, as for many that follow in other figures, represents the best fit by a 6th order polynomial to the experimental data. Actual daily values were scattered about this best-fit curve. To enhance the ability to see differences in data sets for some figures, only the final fitted curves are shown without the individual data points.

Figure 26: Ambient Temperature during Testing



Source: Concurrent Technologies Corporation

Figure 27: Energy Efficiency over Time



Source: Concurrent Technologies Corporation

As expected, as ambient temperature increased, so did the battery operating temperature; the battery operating temperatures exceeded that of the ambient. Interestingly, as the ambient temperature increased, the amount by which the battery temperature exceeded the ambient temperature decreased. This is attributed to improved energy efficiency at higher operating temperatures due to reduced internal cell resistance, yielding lower electrical resistance energy losses and, therefore, a lower net increase in battery pack temperature.

Various temperature values are shown in Table 16. The values use the ambient temperature as a reference, and the values shown represent the difference in the measured temperature and the ambient temperature. Presenting the temperatures in this way normalizes seasonal effects. As expected, the V2G Pack operated at higher temperatures than the Control Pack. Higher operating temperatures are known to accelerate undesirable chemical reactions within lithium-ion batteries, which contributes to battery degradation. Therefore, such temperature-related effects are expected to be more significant in the V2G Pack. The higher operating temperatures of the V2G Pack also contributed to it having higher energy efficiencies than the Control Pack, as mentioned above and discussed in greater detail below.

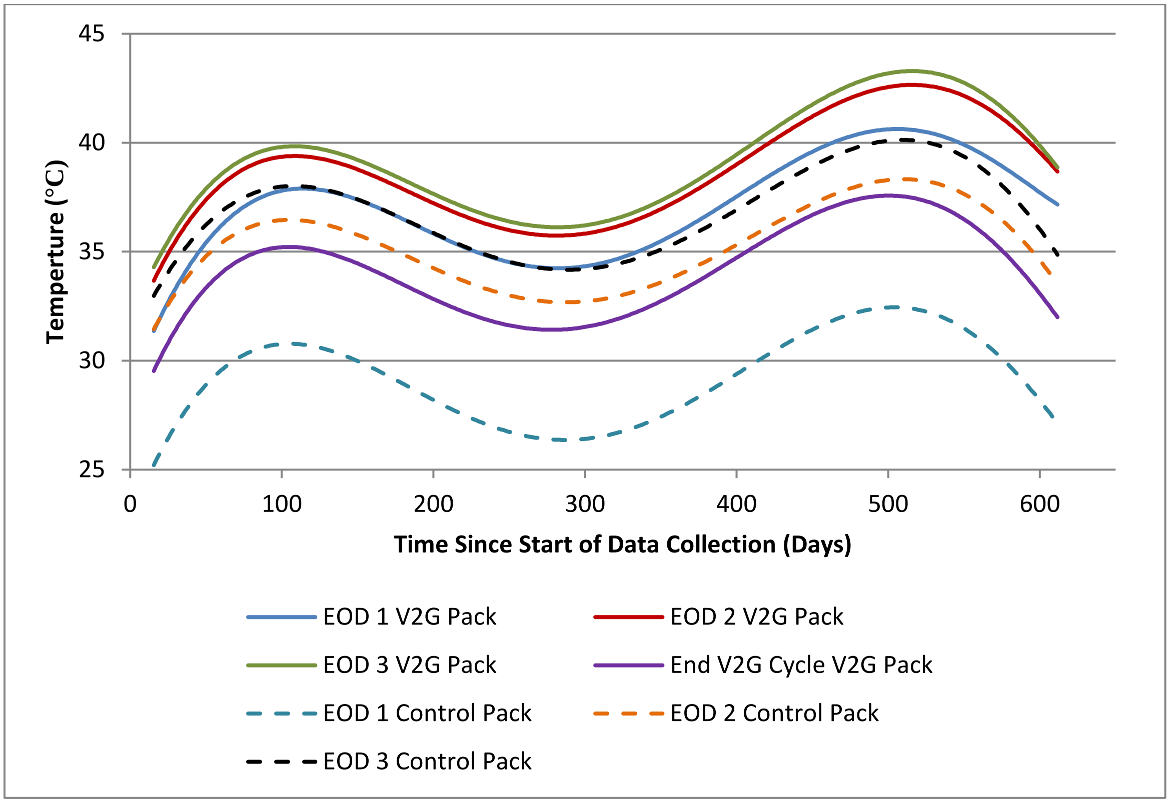
Table 16: Battery Pack Temperatures

Measurement Location/Value	V2G Pack Temperature above Ambient (°C)	Control Pack Temperature above Ambient (°C)
Mean of maximum values: SOH Profile	10.4	6.9
Maximum at end of discharge: SOH Profile	15.2	9.2
Mean maximum values: Standard Test Profile	19.6	12.7
End of Drive Cycle 1 minimum/maximum	14.7 / 20.6	7.8 / 11.7
End of Drive Cycle 2 minimum/maximum	16.0 / 22.6	13.3 / 18.2
End of Drive Cycle 3 minimum/maximum	16.3 / 23.2	14.5 / 20.2

Source: Concurrent Technologies Corporation

One additional factor can be noted regarding the temperatures after each of the drive cycles. In both battery packs, the temperature is greater after each successive drive cycle. This effect is clearly seen in Figure 28, which plots battery pack temperatures at the end of each drive or V2G cycle for both batteries. The gain in temperature between the end of the first two cycles was significantly lower than the temperature gain between the second and third drive cycle. Presumably, this was due to the pack temperatures not returning to an equilibrium value between drive cycles; in other words, the battery packs were still cooling off when the next drive cycle began. Note that the overall gain in operating temperature from the end of the first drive cycle to the end of the last drive cycle is 1.6 / 2.6 °C (minimum / maximum values) for the V2G Pack, while the increase is significantly larger for the Control Pack at 6.7 / 8.5 °C. This suggests the V2G battery pack did not have sufficient time to cool off between the V2G cycle and the start of the first drive cycle. Thus, the V2G battery pack remained at a higher operating temperature during the entire test period. Another observation from Figure 28 is the temperatures at the end of all V2G battery pack drive cycles are greater than the end of the V2G cycle, which suggests that the drive cycle is more aggressive to the battery packs than the V2G cycle.

Figure 28: Mean Pack Temperatures at End of Drive and V2G Cycles



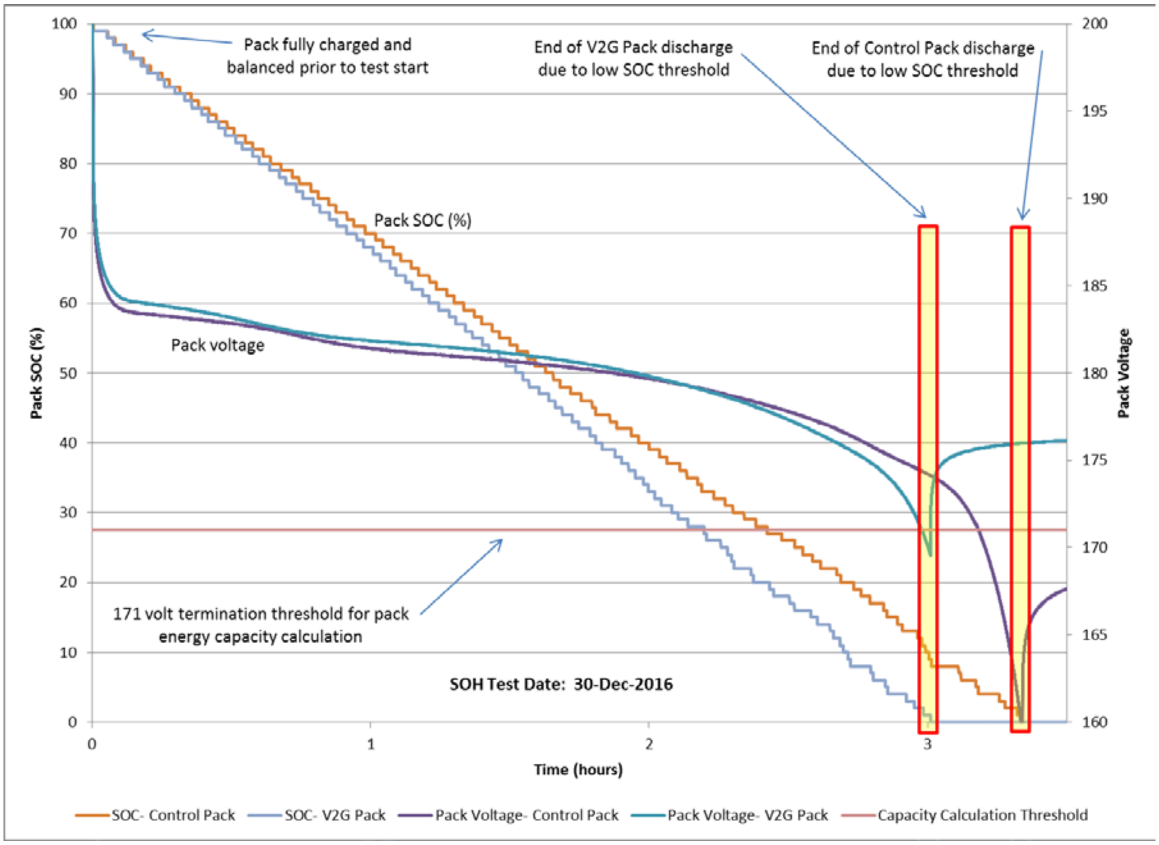
Source: Concurrent Technologies Corporation

State-of-Health Capacity Measurements

The primary means of quantifying battery pack capacity fade throughout testing was periodic execution of the SOH test cycle, as mentioned above.

Figure 29 illustrates the results of the final SOH test run, conducted on December 30, 2016. This graph shows the additional V2G Pack capacity fade that transpired during the laboratory testing activity. The V2G Pack voltage and SOC diminish more rapidly during this test run than the Control Pack. This is a clear indication the V2G Pack has less energy capacity than the Control Pack.

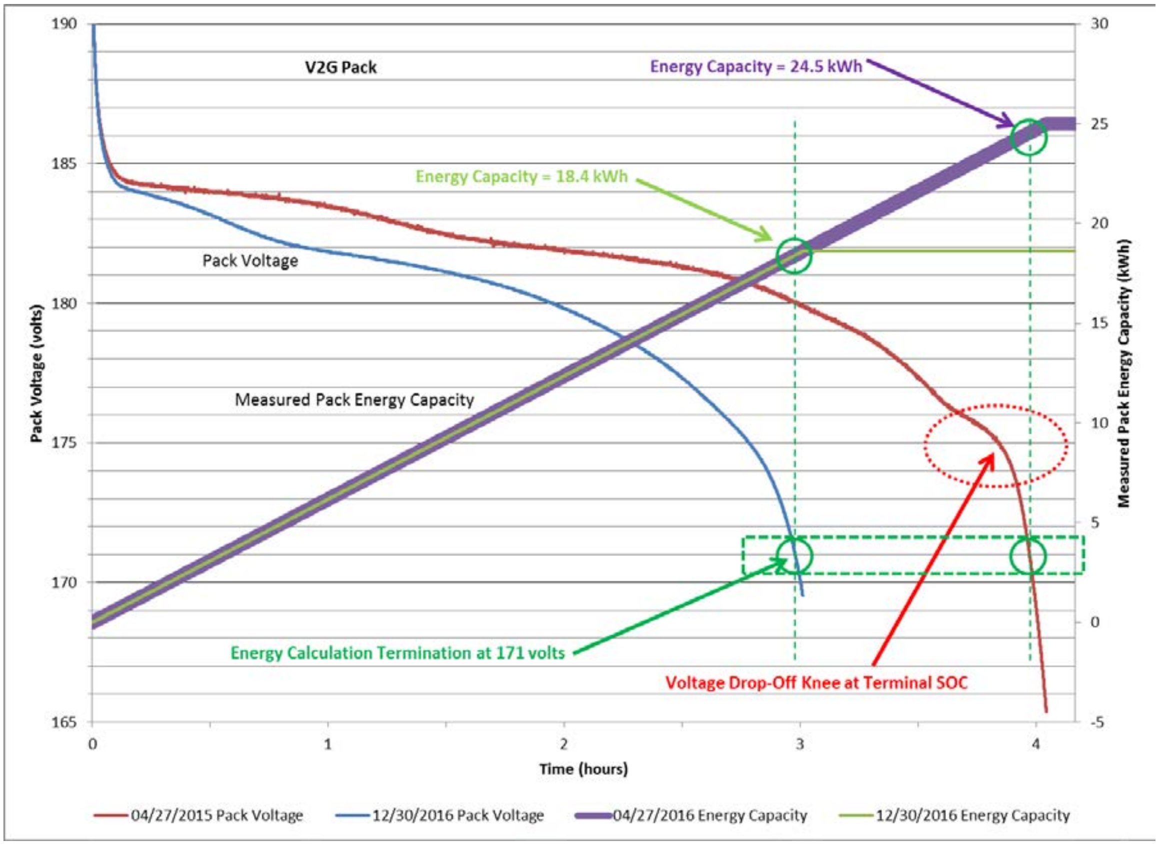
Figure 29: Specimen SOH Test Run Details



Source: Concurrent Technologies Corporation

Figure 30 further illustrates the measured V2G Pack capacity fade that transpired between the initial and final SOH test runs. The pack voltage dropped to the 171-volt energy calculation threshold more rapidly during the final test run on December 30, 2016, at approximately three hours from the beginning of the test cycle, whereas the same threshold occurred nearly an hour later during the initial test run on April 27, 2015. The resultant pack capacity measurement for these two test runs shows a value of 24.5 kWh for the initial test run and a value of 18.4 kWh for the final test run.

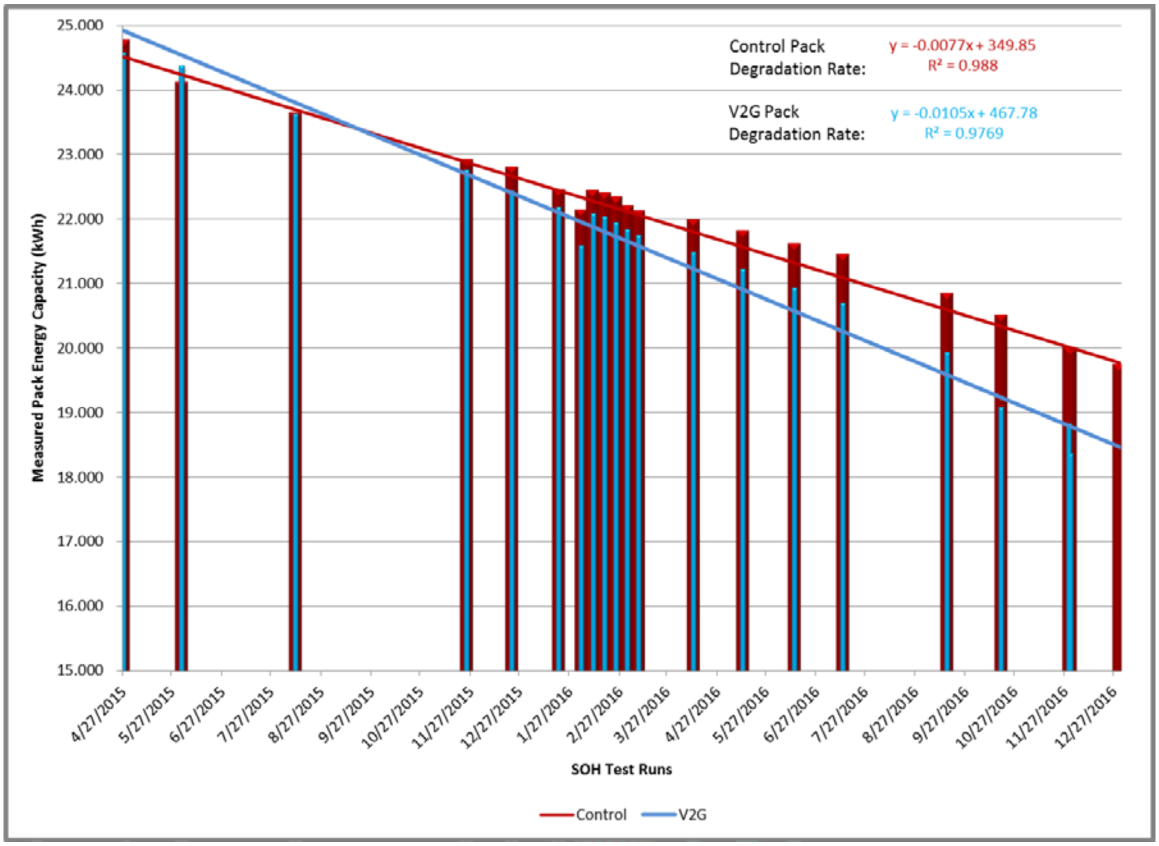
Figure 30: Comparison of Initial and Final SOH Test Runs



Source: Concurrent Technologies Corporation

Figure 31 quantifies the energy capacity degradation for both the Control and V2G Packs from the first through the last test runs. The trend lines and corresponding formulas show the V2G Pack experienced a higher rate of energy capacity degradation from a purely chronological perspective. This is logical given the higher quantity of executed energy transfers (charge and discharge) the V2G Pack experienced.

Figure 31: Raw Pack Energy Capacity

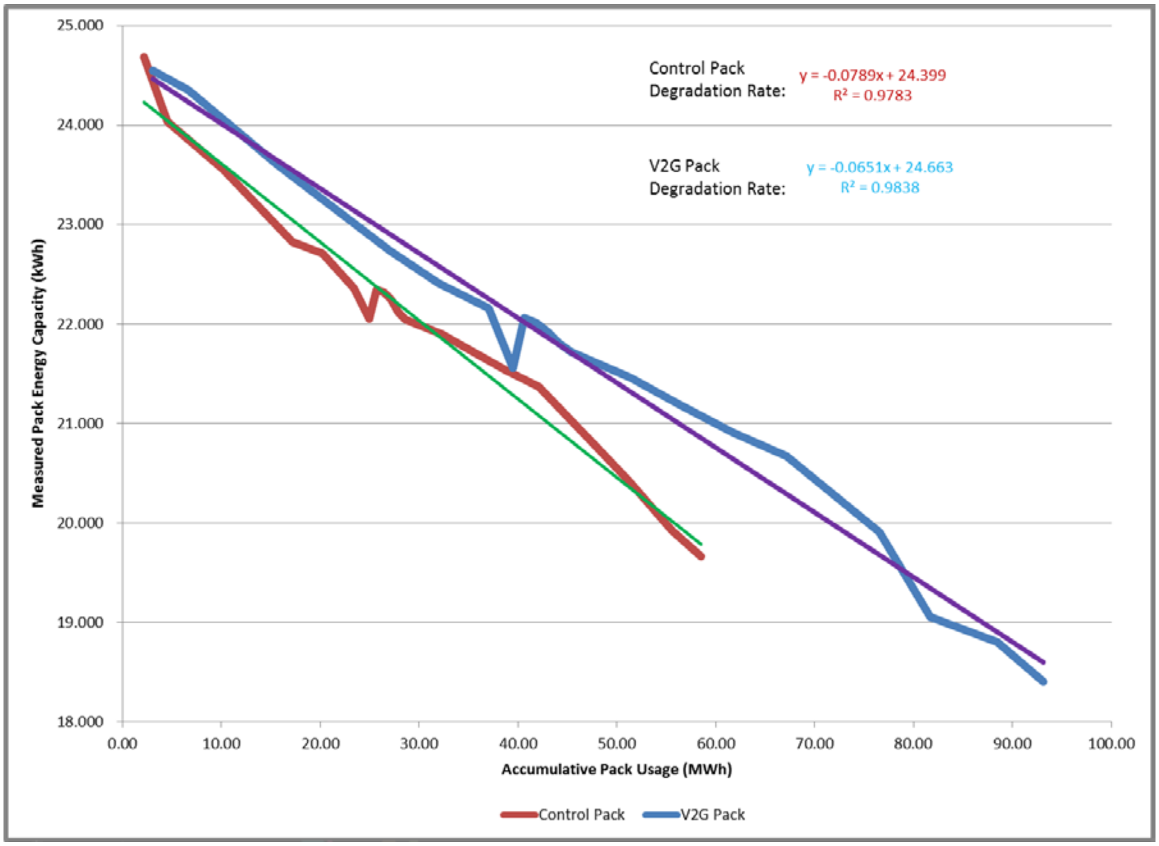


Source: Concurrent Technologies Corporation

However, when the quantity of energy executed by each pack is considered, the capacity degradation is further characterized, as shown in Figure 32. This graph shows the relationship between measured energy capacity and accumulated use. This assessment yields further insight that indicates the capacity of the Control Pack experienced a higher rate of degradation per accumulated use as quantified using a best-fit linear trace (purple and green lines) and their corresponding formulas. As discussed in the Driving and V2G Cycle Comparison Section, several factors affect battery degradation, and usage is just one of those factors. This could be attributed to the drive cycle being more demanding or the time the Control Pack was at float charge.

The trace for each pack demonstrates a downward dip that resulted from much lower pack temperatures during the February 3, 2016, test run.

Figure 32: Energy Capacity vs. Accumulated Use



The accumulated use and capacity fade is reasonable when compared to the battery manufacturer's predicted cycle life at various depths of discharge. The predicted energy throughput based on a C/2 discharge to 90 percent DOD at ambient temperature is approximately 138 megawatt-hours (total energy). Because this is a much less aggressive cycle compared to the driving / V2G cycles used in testing for the present study, the total energy for the V2G and Control Packs of 93.1 megawatt-hours and 58.5 megawatt-hours, respectively is considered to be reasonable.

Aging Effects on Discharge Capacity

SOH data were used to establish discharge capacity. Figure 33 shows the single-factor effect of calendar aging (i.e., time) on discharge capacity. Deviations from a straight line in this figure are in the opposite direction of the time vs. ambient temperature curve shown in Figure 26, suggesting that temperature effects are important to discharge capacity. The most appropriate temperature to consider for this analysis is the mean battery pack temperature, T_P. Upon analyzing the experimental data, both time and mean pack temperature were found to account for the overwhelming majority of the variability in discharge capacity. The empirical equations for each battery pack are as follows.

$$\text{V2G Pack: } C = 23.1 - 0.0103t + 0.0638T_P - 4.13\times10^{-6}(t - 350)(t - 350) \qquad (1)$$

$$R^2 = 0.998$$

$$\text{Control Pack: } C = 23.0 - 0.00736t + 0.0616T_P - 2.30\times10^{-6}(t - 350)(t - 350) \qquad (2)$$

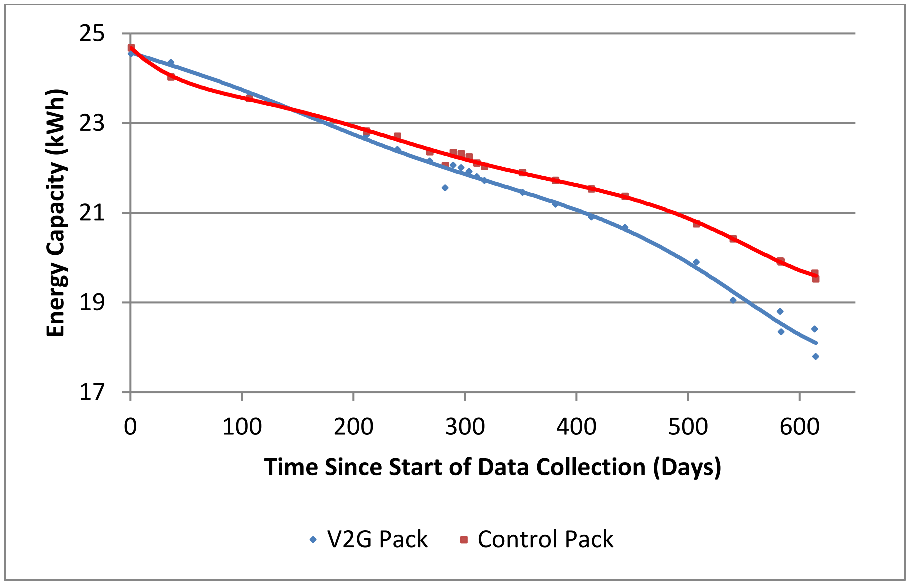
$$R^2 = 0.997$$

C = Discharge capacity (kWh)

t = Time (days from April 27, 2015)

T_P = Mean pack temperature (°C)

Figure 33: Discharge Capacity over Time



Source: Concurrent Technologies Corporation

From equations (1) and (2), pack differences can be computed in the time rate of change of discharge capacity by looking at the coefficients on time, t. Specifically, the aging of the V2G Pack is 1.40 (= 0.0103/0.00736) times that of the Control Pack. In addition to the increased mean time rate of change of discharge capacity for the V2G Pack, it also exhibits a larger effect with respect to the t^2 term, meaning that the time rate of change of degradation is also more rapid for the V2G Pack compared to the Control Pack. In other words, the rate of degradation (represented by the t^2 coefficient) is slightly nonlinear and increases in time. The minor difference between the coefficients on the pack temperature is likely due to the slightly different mean battery temperatures observed during the test period.

Vehicle manufacturers commonly refer to the vehicle battery pack end-of-life when the remaining energy capacity is 70–80 percent of original nameplate. From equations (1) and (2), one can predict the life of each of the battery packs, assuming the same charge/discharge cycles are repeated throughout the life of the battery packs. Using equations (1) and (2), the time required to reach 80 percent of original capacity for the V2G Pack is 502 days, while it takes the Control Pack 620 days[7] to reach 80 percent of its original capacity. In both cases, the mean overall temperatures during SOH evaluations (T_P = 25.2 °C for the V2G battery pack and T_P = 22.2 °C for the Control Pack) were used for the battery pack temperatures, T_P. In addition, the discharge capacity at t = 0 (which was 24.55 kWh for the V2G Pack and 24.68 for the Control Pack) was used to represent the nameplate discharge capacity. In other words, the estimated V2G battery life is reduced by 19 percent over the Control battery pack for the charge cycles incurred during this test. Note that the V2G cycle used in the testing represented extreme V2G cycling as did the driving cycles. Therefore, degradation in battery life would likely be less than that noted here for actual V2G and driving implementation.

NCC Capacity Measurements

During testing, evaluating capacity fade based on the battery nameplate capacity became important. The manufacturer rates the battery capacity on a 1/5 C discharge at room temperature (~23 °C). Lower temperatures and/or higher discharge rates will, as with all battery chemistries, reduce the available capacity. Three NCC tests were performed, with the second and third occurring on the same day after allowing enough time for the pack temperature to stabilize after the first of these two measurements. As seen in Table 17, the V2G Pack had a capacity fade of 25 percent of nameplate, while in Table 18, the Control Pack had a capacity fade of 16 percent. Additionally, the average minimum and maximum temperatures have been captured for each test. As with the temperatures associated with the standard and SOH test data, the values for the V2G cycle are higher than those for the Control Pack. However, here the difference is not due to the extra load requested of the batteries during the NCC testing. It is most likely due to the increased internal electrical resistance resulting from greater battery degradation in the V2G Pack compared to the Control Pack. Note that all three of the NCC tests were near or at the end of the battery testing period when battery degradation would have been at its highest for both battery packs.

Table 17: V2G Pack Nameplate Capacity Comparison Test Results

Test Date	V2G Pack			
	Capacity (kWh)	Average Minimum Temperature (°C)	Average Maximum Temperature (°C)	% of Rated Capacity
11/14/2016	19.43	25.8	29.7	78.6%
1/2/2017	18.42	16.1	19.0	74.5%
1/2/2017	18.45	16.8	20.1	74.6%

Source: Concurrent Technologies Corporation

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[7] Statisticians warn against extrapolating curve fits beyond the range of values studied. For the current assessment, the range was 0 to 614 days. The authors do not expect significant differences in behavior of the Control Pack when using equation (2) to extrapolate to 620 days.

Table 18: Control Pack Nameplate Capacity Comparison Test Results

Test Date	Control Pack			
	Capacity (kWh)	Average Minimum Temperature (°C)	Average Maximum Temperature (°C)	% of Rated Capacity
11/14/2016	21.30	23.3	26.2	86.1%
1/2/2017	20.69	14.8	17.5	83.7%
1/2/2017	20.73	15.8	18.5	83.8%

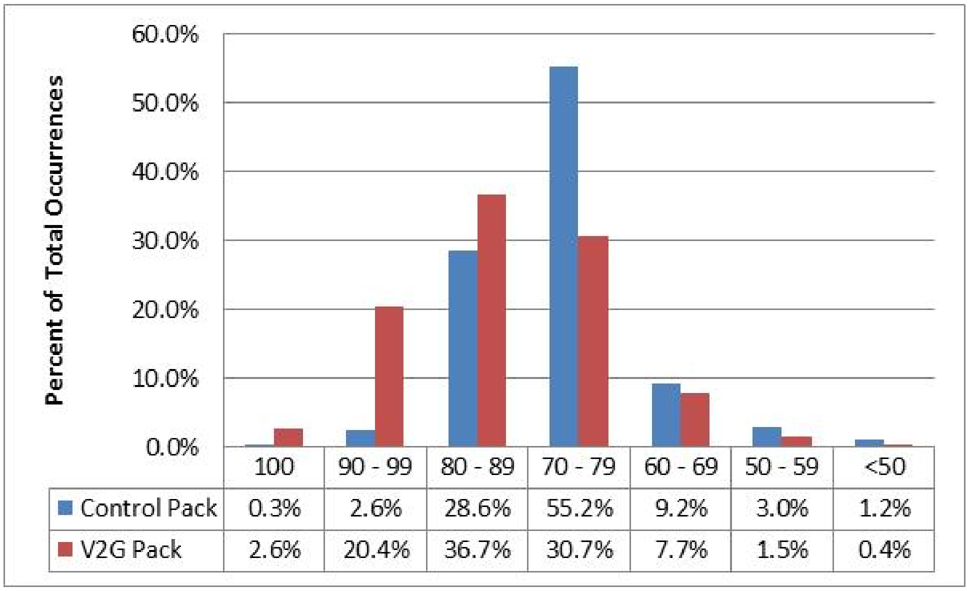
Source: Concurrent Technologies Corporation

As seen in Table 17, the V2G Pack is 74.6 percent of the specified battery capacity at the end of the test period. Based on the common standard throughout industry, this battery pack should be replaced if the driving and V2G cycles were to continue. The Control Pack has shown less capacity fade with 83.8 percent of rated capacity. It should be noted that this capacity method is different than the SOH capacity measurement. The NCC test results show the capacity fade for both battery packs. There is a more than 9 percentage point increase in capacity fade for the V2G Pack due to several of the degradation factors discussed earlier.

Depth of Discharge

Figure 34 shows a comparison of the DOD for each battery pack as a percentage of total DOD occurrences during the entire test period. Sixty percent of the V2G Pack DOD occurrences were greater than 80 percent, while only 32 percent of the Control Pack DOD occurrences were greater than 80 percent. The mean DOD was 81.5 and 76 percent for the V2G and Control Packs, respectfully. The standard deviations were 10.9 and 9.3 percentage points. The generally greater DOD for the V2G Pack is a contributing factor to its greater rate of degradation. When the cyclic charge/discharge pattern is repeated, increased DOD is associated with a lowered energy storage capacity, which develops as the battery is used. The increased DOD required to accomplish a desired battery usage profile degrades the battery at an increasing rate and may be responsible for the nonlinear rate of degradation represented by the second-order term in time shown in equations (1) and (2).

Figure 34: Depth of Discharge Comparison



	100	90 - 99	80 - 89	70 - 79	60 - 69	50 - 59	<50
🟦 Control Pack	0.3%	2.6%	28.6%	55.2%	9.2%	3.0%	1.2%
🟥 V2G Pack	2.6%	20.4%	36.7%	30.7%	7.7%	1.5%	0.4%

Source: Concurrent Technologies Corporation

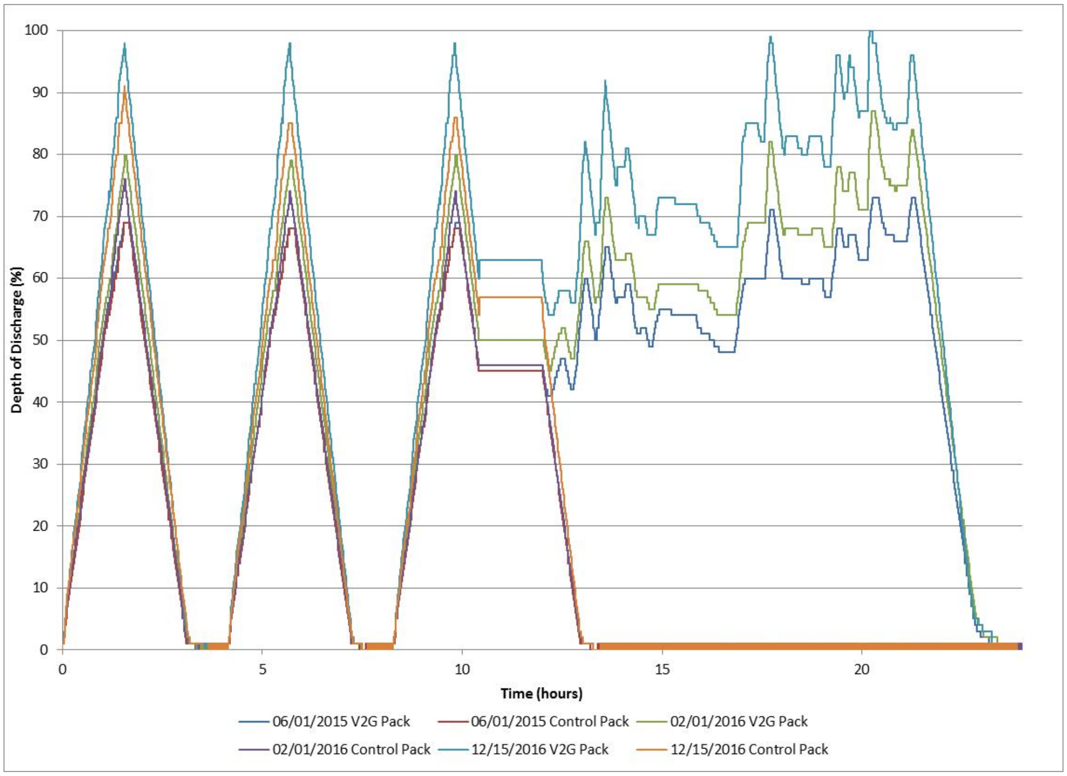
The standard test profile was developed to achieve a DOD of 74 percent for each drive cycle with the understanding that, as the battery packs degraded, the DOD would increase. Similarly, the V2G profile was developed to achieve a DOD of 71 percent. Table 19 provides a summary of three test runs from an early, mid and late test event. Note that the DOD was consistent between the V2G and Control Packs on the early specimen. As the testing continues, one can see an increase in the DOD during the middle specimen for both packs, suggesting that the capacity of the battery packs is fading. The late specimen shows a further increase in the DOD for both battery packs. Furthermore, the difference between the V2G Pack and the Control Pack DOD continues to increase over time. Additionally, note the higher DOD for Drive Cycle 1 for the Control Pack. This is most likely an effect of low battery temperature experienced in the Control Pack during Drive Cycle 1 as discussed in the Temperature Comparisons Section. Figure 35 shows the DOD during a 24-hour period for specific test dates as identified in Table 19. This graph clearly shows the increased DOD required to achieve the same test profile.

Table 19: Summary Information – Observed Depth-of-Discharge

Observations:		**V2G Pack Maximum DOD (%)**	**Control Pack Maximum DOD (%)**
06/01/2015			
(Early specimen)	Drive Cycle 1	69	69
	Drive Cycle 2	68	68
	Drive Cycle 3	69	68
	V2G Cycle	73	N/A
02/01/2016			
(Middle specimen)	Drive Cycle 1	80	76
	Drive Cycle 2	79	74
	Drive Cycle 3	80	74
	V2G Cycle	87	N/A
12/15/2016			
(Late specimen)	Drive Cycle 1	98	91
	Drive Cycle 2	98	85
	Drive Cycle 3	98	86
	V2G Cycle	100	N/A

Source: Concurrent Technologies Corporation

Figure 35: Observed 24-hour DOD for Specific Test Dates



Source: Concurrent Technologies Corporation

Degradation in the DOD Domain

Another method used to identify degradation was to account for the accumulated (i.e., total) DOD during the test period. Total DOD had a very strong linear relationship with total energy. For both battery packs, the R^2 value for these linear relationships was 0.999, indicating that the two variables have virtually no orthogonality between them. Therefore, conclusions about the effects of one of the two variables would be essentially identical to the effects of the other. Consequently, no further comments will be made in this report about the degradation effects of totalized DOD; instead, evaluations will continue with totalized energy.

As the battery packs continued to be exercised, the DOD increased to accomplish the required driving and V2G demands. These effects can be clearly seen in Figure 36, which shows the DOD at the end of each drive and V2G cycle for the V2G Pack. Note the DOD at the end of the V2G cycle is greater than any of the driving cycles. (An exception can be seen at the end of the test period when nearly 100 percent DOD was reached for all cycles.) However, it must be kept in mind that the SOC at the start of the V2G cycle was only 55 percent, while the drive cycles started at 100 percent SOC. This means that the actual delivery of energy is 45 percentage points less during the V2G cycle based upon the SOC at the end of the V2G cycle. In addition, the DOD for each of the three drive cycles is nearly identical to the V2G cycle. Pack temperature effects appear to be statistically significant for the DOD. When included in the multi-variable statistical analysis, the resulting least squared fit to the data is as follows.

V2G Pack (End Drive Cycle 1): $D = 79.8 + 0.0524t - 0.480T_P + 0.0000566(t - 323)(t - 323)$ (3)

$R^2 = 0.990$

V2G Pack (End Drive Cycle 2): $D = 75.3 + 0.0511t - 0.350T_P + 0.0000480(t - 323)(t - 323)$ (4)

$R^2 = 0.987$

V2G Pack (End Drive Cycle 3): $D = 76.1 + 0.0518t - 0.382T_P + 0.0000506(t - 324)(t - 324)$ (5)

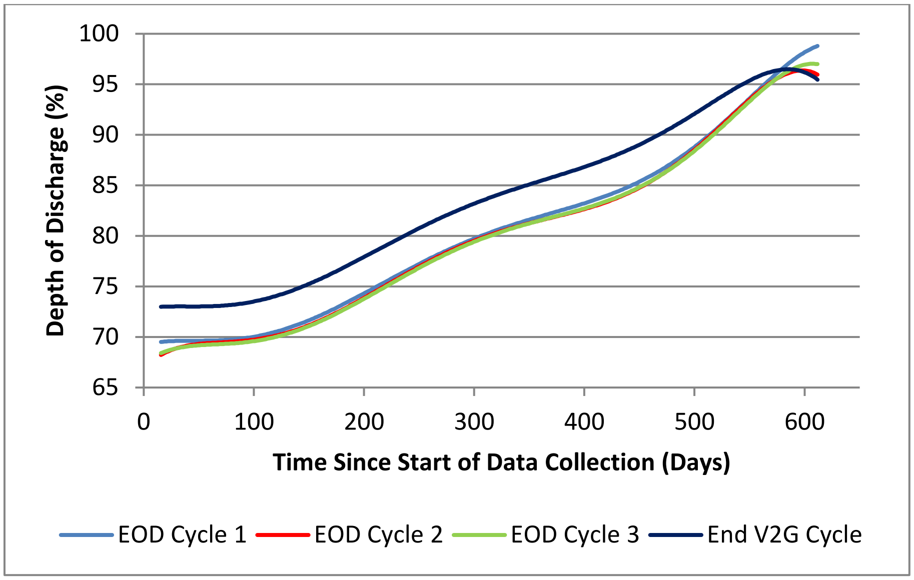
$R^2 = 0.989$

V2G Pack (End V2G Cycle): $D = 76.9 + 0.0464t - 0.236T_P + 0.0000224(t - 324)(t - 324)$ (6)

$R^2 = 0.985$

D = Depth of discharge (%)

Figure 36: DOD at End of Drive (EOD) and V2G Cycles for V2G Pack



Source: Concurrent Technologies Corporation

Similar DOD data for the Control Pack are plotted in Figure 37. Again, the DOD increases with battery use, and temperature effects appear to be significant. For the Control Pack, however, the degradation did not reach the point where the full charge was needed to achieve the drive cycles. The DOD is lower for each successive drive cycle; the difference between Drive Cycle 1 and Drive Cycle 2 is significantly greater than between Drive Cycle 2 and Drive Cycle 3. This follows the same trend as the mean battery temperature from cycle to cycle. Therefore, the apparent improvement in battery performance (as measured by DOD) for Drive Cycles 2 and 3 is attributed to the higher mean battery temperatures during these drive cycles. The resulting least squared fit to the DOD data for the Control Pack are as follows.

Control Pack (after Drive Cycle 1): $D = 73.2 + 0.0332t - 0.233T_P + 0.0000460(t - 323)(t - 323)$ (7)

$R^2 = 0.980$

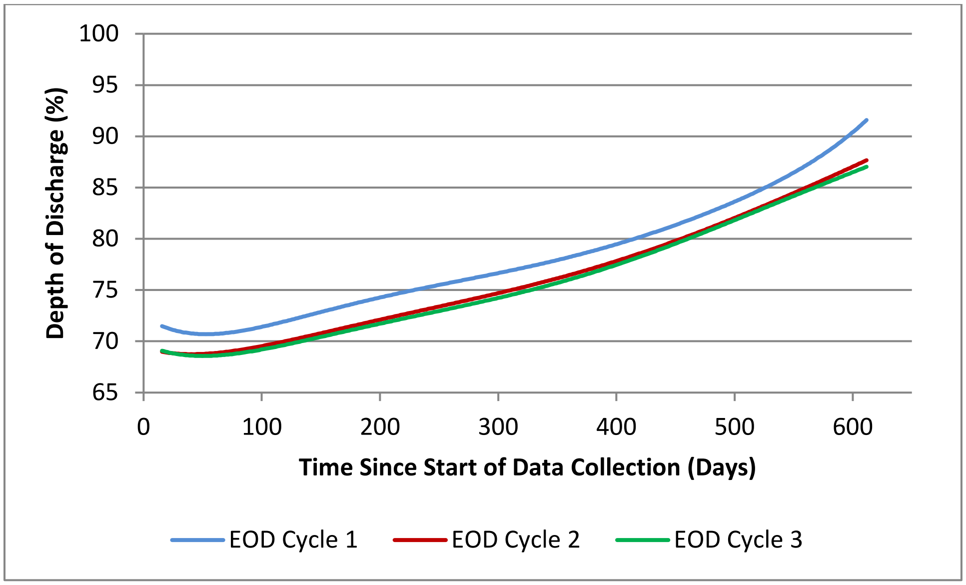
Control Pack (after Drive Cycle 2): $D = 67.5 + 0.0326t - 0.0921T_P + 0.0000355(t - 323)(t - 323)$ (8)

$R^2 = 0.984$

Control Pack (after Drive Cycle 3): $D = 66.1 + 0.0325t - 0.0571T_P + 0.0000368(t - 324)(t - 324)$ (9)

$R^2 = 0.985$

Figure 37: DOD at End of Drive Cycles for Control Pack



Source: Concurrent Technologies Corporation

Use (Total Energy)

As introduced earlier, the accumulated usage of a battery pack, and specifically Total energy, is a factor in capacity fade. Table 20 summarizes the observed energy use of both battery packs using actual test data for standard test runs on three separate test dates: early, mid and late test dates. Figure 38 summarizes the accumulative absolute energy usage.

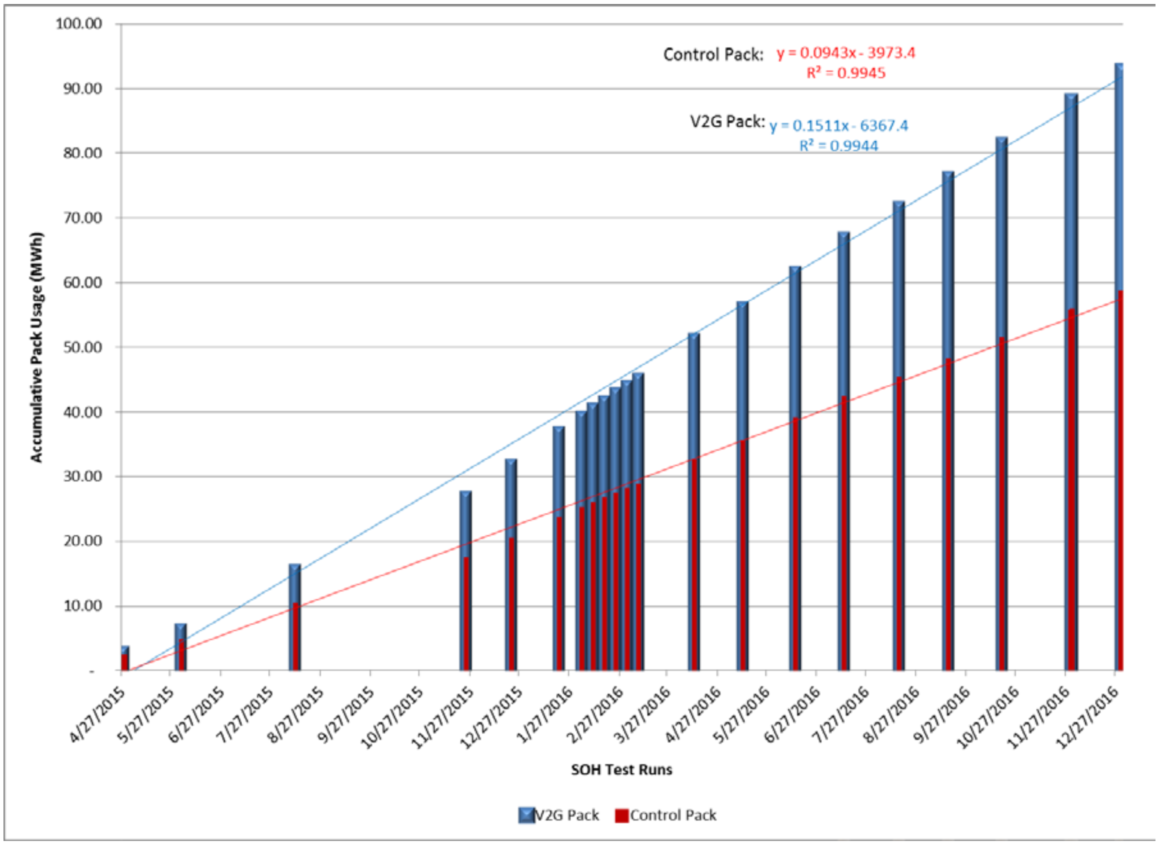
The V2G Pack clearly experienced greater total energy than the Control Pack during the course of laboratory testing. Each standard test run contributed approximately 189 kWh of V2G Pack usage and 115 kWh of Control Pack usage. The resulting accumulative absolute energy was 93.13 MWh for the V2G Pack and 58.52 MWh for the Control Pack, or 34.61 MWh additional energy use for the V2G Pack over the course of the testing activity. This was 59 percent more usage than the Control Pack. However, as discussed in the State-of-Health Capacity Measurements Section, while this total energy disparity did result in more energy capacity degradation for the V2G Pack, the degradation rate based on total energy was greater for the Control Pack. This clearly illustrates other usage traits are at play in defining pack energy capacity degradation.

Table 20: Summary Information – Observed Energy

06/01/2015		**V2G Pack (kWh)**			**Control Pack (kWh)**		
(Early specimen)		**Energy In**	**Energy Out**	**Total Energy**	**Energy In**	**Energy Out**	**Total Energy**
	Drive Cycle 1	19.89	(18.58)	38.47	19.80	(18.47)	38.27
	Drive Cycle 2	19.81	(18.58)	38.39	19.72	(18.47)	38.19
	Drive Cycle 3	7.70	(18.58)	26.28	19.84	(18.54)	38.37
	All Drive Cycles	47.40	(55.74)	103.14	59.36	(55.48)	114.84
	V2G Cycle	50.17	(36.05)	86.22	N/A	N/A	N/A
	Totals	***97.57***	***(91.79)***	***189.36***	***59.36***	***(55.48)***	***114.84***
02/01/2016		**V2G Pack (kWh)**			**Control Pack (kWh)**		
(Middle specimen)		**Energy In**	**Energy Out**	**Total Energy**	**Energy In**	**Energy Out**	**Total Energy**
	Drive Cycle 1	19.91	(18.55)	38.46	20.05	(18.44)	38.48
	Drive Cycle 2	19.89	(18.54)	38.43	19.91	(18.51)	38.42
	Drive Cycle 3	7.71	(18.56)	26.26	20.04	(18.49)	38.53
	All Drive Cycles	47.51	(55.65)	103.16	59.99	(55.44)	115.43
	V2G Cycle	50.66	(36.05)	86.71	N/A	N/A	N/A
	Totals	***98.17***	***(91.70)***	***189.87***	***59.99***	***(55.44)***	***115.43***
12/15/2016		**V2G Pack (kWh)**			**Control Pack (kWh)**		
(Late specimen)		**Energy In**	**Energy Out**	**Total Energy**	**Energy In**	**Energy Out**	**Total Energy**
	Drive Cycle 1	20.02	(18.45)	38.47	20.44	(18.60)	39.04
	Drive Cycle 2	19.99	(18.47)	38.45	19.90	(18.34)	38.24
	Drive Cycle 3	7.71	(18.46)	26.17	20.50	(18.49)	38.99
	All Drive Cycles	47.71	(55.38)	103.09	60.84	(55.43)	116.27
	V2G Cycle	49.75	(34.86)	84.61	N/A	N/A	N/A
	Totals	***97.46***	***(90.23)***	***187.70***	***60.84***	***(55.43)***	***116.27***

Source: Concurrent Technologies Corporation

Figure 38: Absolute Observed Accumulative Energy for Both Battery Packs



Source: Concurrent Technologies Corporation

Degradation in the Number of Cycles and Use Domains

Another basis for comparing the impact of the V2G cycle is to use the total energy passing through the battery pack. Total energy is defined as the electrical energy passing through the battery pack regardless of its direction (in or out of the battery pack).

Figure 39 shows the single-factor effect of total energy on discharge capacity measured during the SOH tests. The rate of change in capacity measured in this reference frame shows the Control Pack degrading more quickly than the V2G Pack. This is in part due to the compressed calendar aging associated with the Control Pack. However, the difference is likely also due to differences in the aggressiveness of the drive cycle versus the V2G cycle. Aggressiveness is discussed in the Driving and V2G Cycle Comparison Section. As with time-based effects, temperature effects also appear to be significant. The empirical equations describing this multi-variable effect are as follows.

$$\text{V2G Pack: } C = 22.4 - 0.0658E_T + 0.0746T_P \qquad (10)$$

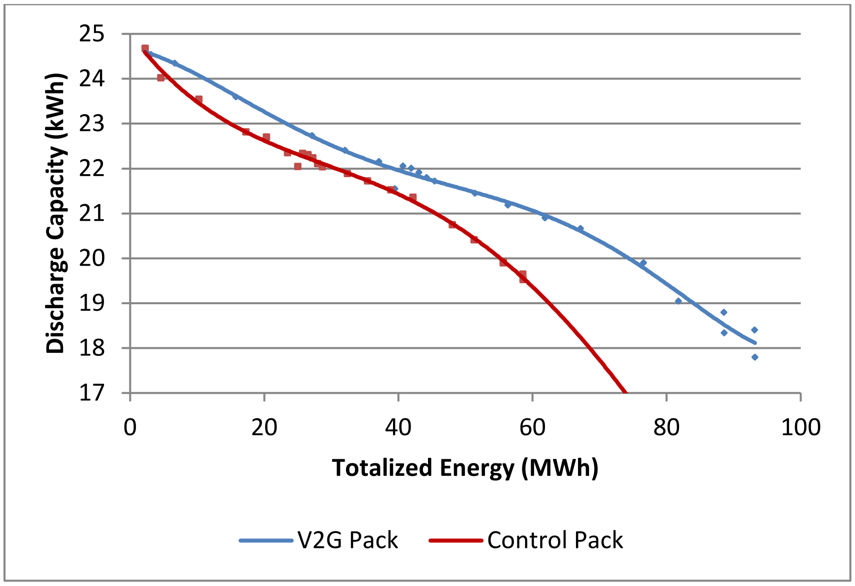
$$R^2 = 0.995$$

$$\text{Control Pack: } C = 22.6 - 0.0756E_T + 0.0698T_P \qquad (11)$$

$$R^2 = 0.994$$

E_T = Total energy (MWh)

Figure 39: Total Energy Effects on Discharge Capacity



Source: Concurrent Technologies Corporation

On a total energy basis, the rate of degradation of the Control Pack is 1.15 (= 0.0756/0.0658) times that of the V2G Pack.

Another method to gauge the impact of cycle count on degradation is to identify discharge capacity as a function of the number of charge/discharge cycles. Figure 40 was developed by accumulating partial discharge amounts at the end of each drive and V2G cycle.[8] This simple one-dimensional plot has curvature characteristic of temperature effects. Therefore, a multi-dimensional curve fit was evaluated using the accumulated cycle count and the mean pack temperature after the end of discharge during the SOH tests. The corresponding least squared curve fit for each battery pack is shown in equations (12) and (13). The coefficients on the cycle count (K) for the V2G Pack is 1.03 (= 0.00380/0.00368) times that of the Control Pack. As with most of the other degradation measures, including the effects of the pack temperature yields an improved fit to the experimental data.

$$\text{V2G Pack: } C = 22.3 - 0.00380K + 0.0674T_P \qquad (12)$$

$$R^2 = 0.995$$

---

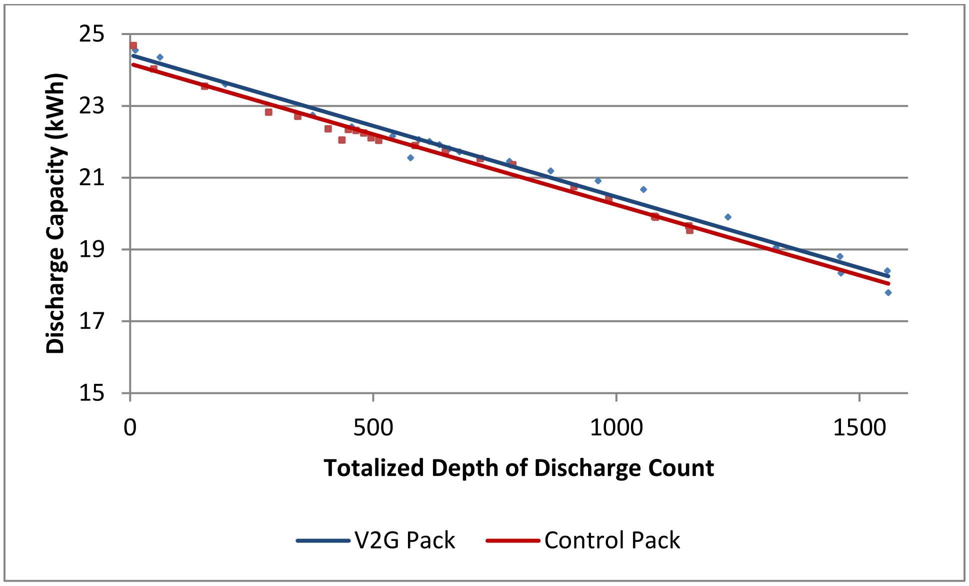
[8] Cycle counts for the V2G cycle accounted for three distinct drops in state of charge: 1) from ~44,000 sec to ~49,500 sec, 2) from ~60,000 sec to ~64,000 sec and 3) from ~72,500 sec to ~73,500 sec. State of charge traces from May 12, 2005 and November 28, 2016 were used to identify the accumulated drop in state of charge (i.e., the cycle count for the actual V2G cycles) for these three distinct regions. Cycle counts for all other dates that included a full V2G cycle were then linearly interpolated/extrapolated using the values from these two dates.

Control Pack: $C = 22.2 - 0.00368K + 0.0754T_P$ (13)

$R^2 = 0.993$

K = Cycle count

Figure 40: Impact of Charge/Discharge Cycling on Discharge Capacity



Source: Concurrent Technologies Corporation

Rate of Change

Another trait of the test cycles is the rate at which the commanded battery pack power changes. Analogous to mechanical systems, higher rates of change (ROC) are theorized to lead to faster degradation than lower rates of change.

To help assess ROC, all ROC values resulting from commanded test cycle power were compiled and assembled into histograms for both packs (Figure 41 and Figure 42). This enabled quantification and visualization of the ROC occurrence and distribution. Statistics were also compiled to further characterize ROC (Table 21). The data are based on a ten-second running average of the one-second commanded power.

Table 21: Rate-of-Change Information Summary; Commanded Power

ROC Information	Driving Segment	V2G Segment
Sample Quantity	5,656	33,323
Maximum Negative ROC	-134%	-16,593%
Maximum Positive ROC	574%	14,150%
Mean Negative ROC	-8.55%	-7.95%
Mean Positive ROC	11.23%	5.87%
Mean ROC	1.47%	-0.41%
Standard Deviation	24%	143%
Mean negative command; entire standard profile; watts	-10,524	
Mean positive command; entire standard profile; watts	9,991	
Command update period, seconds	1	
Assessment averaging period, seconds	10	

Source: Concurrent Technologies Corporation

The histogram data indicates the highest percentage of ROC occurrences as follows:

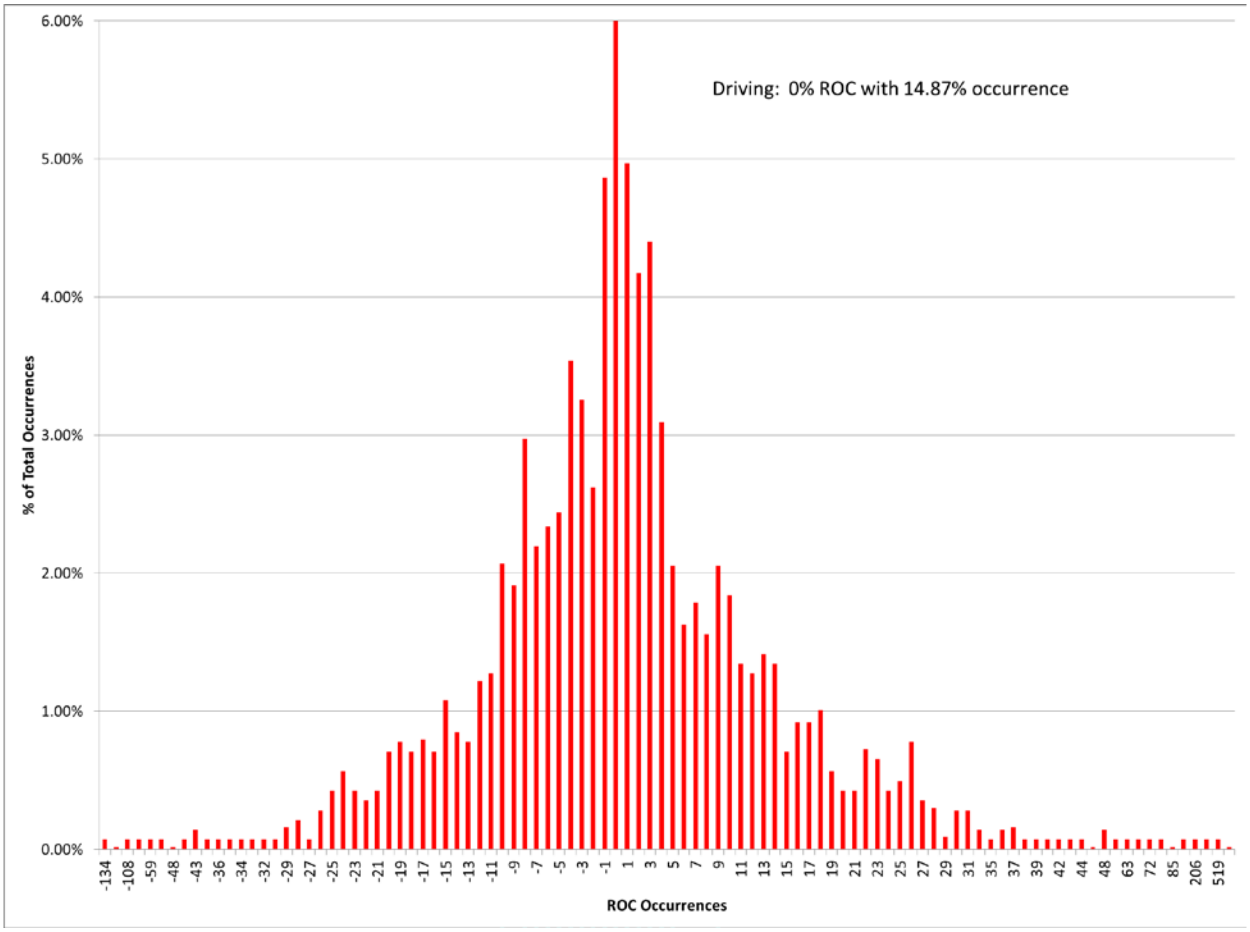
- Driving Segment: 14.87 percent occurrence at 0 percent ROC
- V2G Segment: 51.78 percent occurrence at 0 percent ROC.

The statistical data summary identified key findings.

- Although the V2G segment yields higher maximum ROC values (both positive and negative extremes), the relative number of these extreme values is minute.
- The Driving segment had higher mean ROC, particularly in the positive (charging) direction.
- The Driving segment had a higher overall mean ROC.
- The Driving segment had a much smaller standard deviation.

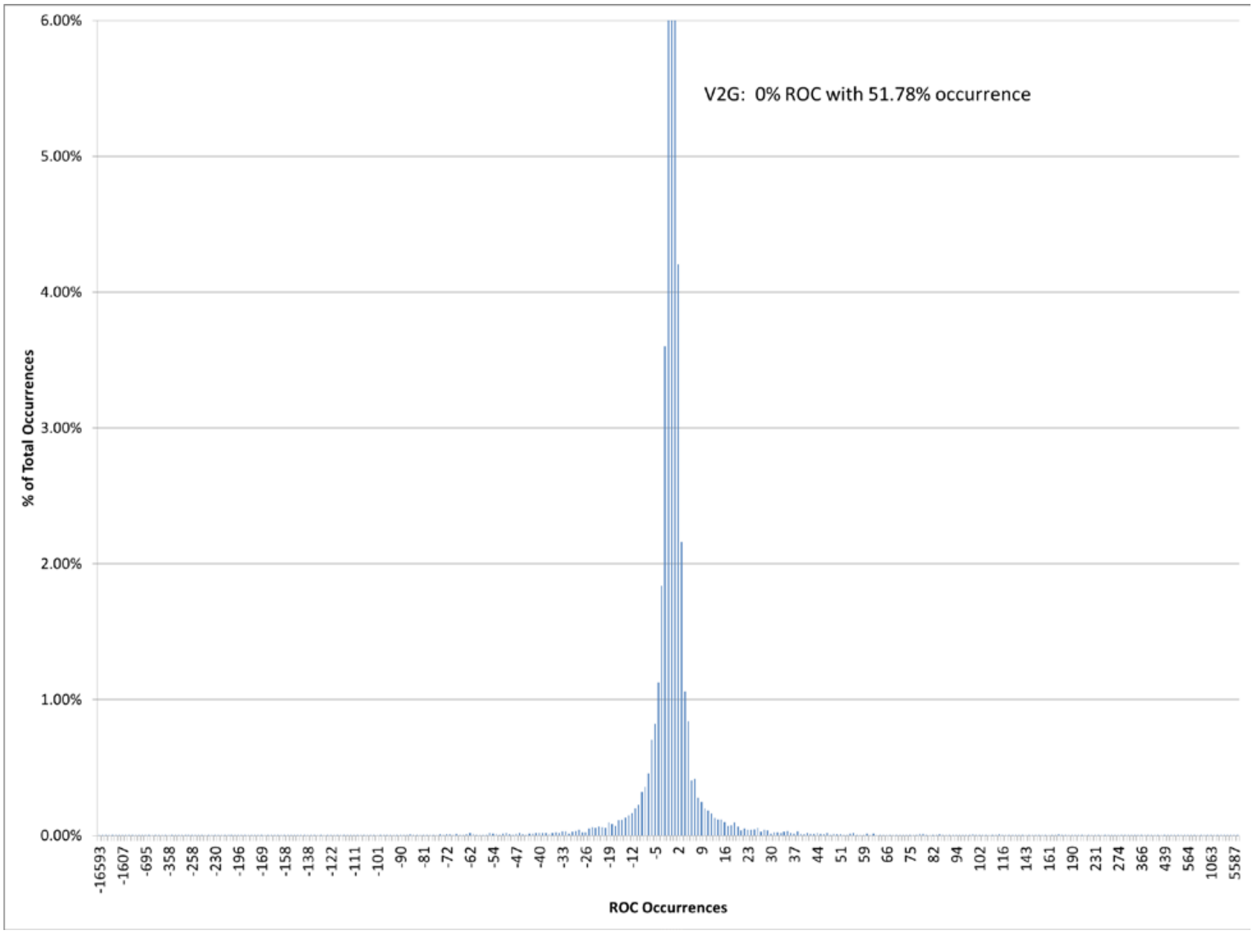
These findings show the Driving segment imposes more pack degradation relative to the ROC test cycle trait.

Figure 41: ROC Distribution of Commanded Power for Driving Segment



Source: Concurrent Technologies Corporation

Figure 42: ROC Distribution of Commanded Power for V2G Segment



Source: Concurrent Technologies Corporation

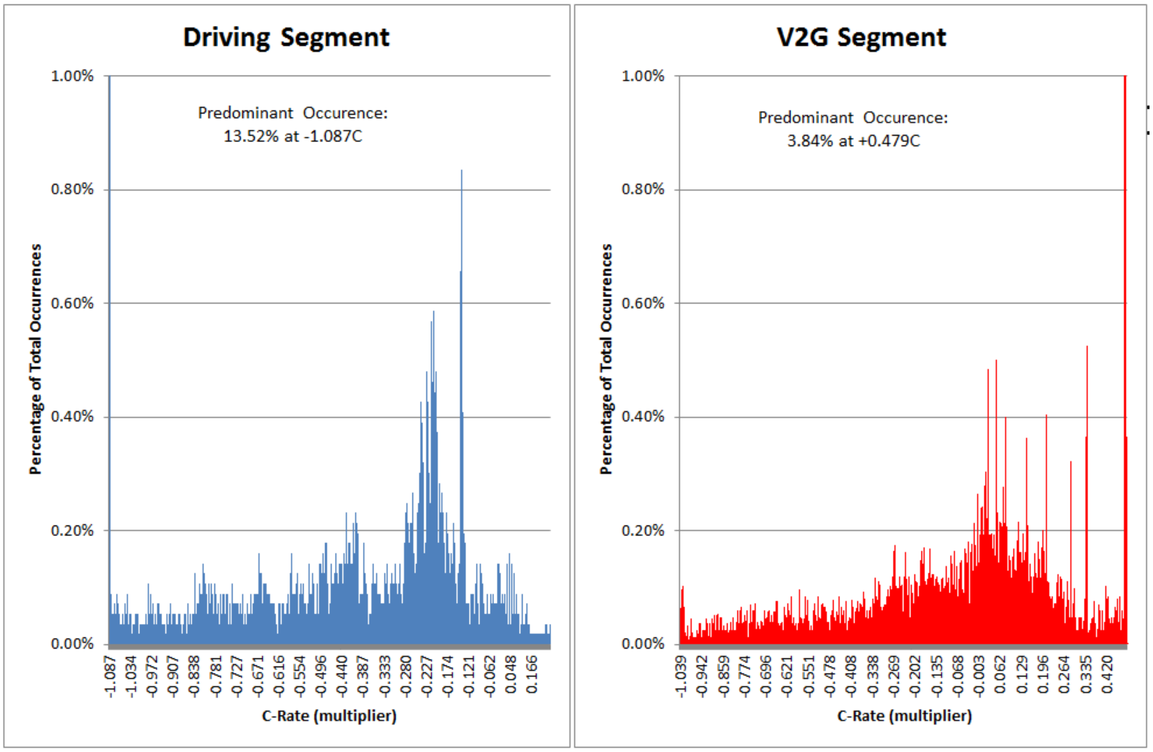
C-Rates

This section discusses an assessment of C-Rates focused on observed performance from three specimens standard test runs. To help assess C-Rates, all C-Rate values resulting from an executed standard test cycle were compiled and assembled into histograms for both packs as shown in Figure 43. This enabled quantification and visualization of the C-Rate occurrence and distribution. Statistics were also compiled to further characterize C-Rate (see Table 22). The histogram data indicates the highest percentage of C-Rate occurrences as follows:

Driving Segment:	13.52 percent occurrence at -1.087C
V2G Segment:	3.84 percent occurrence at +0.479C

The statistical data summary determined that the Driving segment had a substantially larger overall mean C-Rate than the V2G segment (-0.471C vs. -0.033C) or 14.3 times greater than the V2G segment. This finding shows the Driving segment imposes more pack degradation relative to the C-Rate test cycle trait.

Figure 43: Distribution of Observed C-Rates



Note: these are from the observed V2G Pack early specimen data

Source: Concurrent Technologies Corporation

Table 22: C-Rate Statistical Summary

From Observed V2G Pack Early Specimen	Driving Segment	V2G Segment
Sample Quantity	5,656	33,323
Maximum Negative C-Rate	-1.087	-1.039
Maximum Positive C-Rate	0.494	0.491
Mean Negative C-Rate	-0.506	-0.342
Mean Positive C-Rate	0.147	0.233
Mean C-Rate	-0.471	-0.033
Standard Deviation	0.365	0.364
Mean negative C-Rate; entire standard profile	-0.425	
Mean positive C-Rate; entire standard profile	0.273	
Command update period, seconds	1	
Assessment averaging period, seconds	1	
C-Rates are expressed as multiplying factor (e.g., -1.087C)		

Source: Concurrent Technologies Corporation

Aging Effects on Energy Efficiency

Figure 27 shows the single-factor effect of calendar aging (i.e., time) on energy efficiency. The energy efficiency of the V2G battery pack is greater than the Control Pack; the mean energy efficiency for the V2G Pack was 95.8 percent, while the mean energy efficiency for the Control Pack was 95.2 percent. This is primarily due to the higher operating temperature of the V2G Pack; however, differences in the performance of the cells that comprise each battery pack may also have contributed to this difference. The empirical equations for each battery pack are as follows.

$$\text{V2G Pack: } E = 92.7 - 0.00256t + 0.113T_P - 3.88\times10^{-6}(t-323)(t-323) \qquad (14)$$

$$R^2 = 0.920$$

$$\text{Control Pack: } E = 92.0 - 0.00110t + 0.122T_P - 2.72\times10^{-6}(t-323)(t-323) \qquad (15)$$

$$R^2 = 0.917$$

E = Energy efficiency (%)

JMP offsets higher-order terms by the mid-range of the factor among the data entries. This can be seen in the t^2 term, which is offset by 323 days. It is best to keep the equations in this format when identifying differences between the two battery packs. By doing so, one can more accurately identify the impact of all factors in the empirical equation by comparing the coefficients on individual terms.

The coefficient on the time parameter gives an indication of the "average" time ROC of a response variable. In this case, the time ROC of energy efficiency for the V2G Pack is 2.33 (= 0.00256/0.00110) times that of the Control Pack. Although the mean V2G Pack energy efficiency is greater than the Control Pack, given sufficient additional cycling during laboratory testing, the instantaneous energy efficiency of the Control Pack will eventually surpass the V2G Pack as a result of this difference. This effect can be seen in Figure 27 where the energy efficiency curves draw closer together as time progresses. The larger coefficient on the Control Pack temperature term suggests that the energy efficiency of this battery pack is more sensitive to swings in temperature. The larger coefficient on the t^2 term for the V2G Pack indicates the time ROC of degradation in energy efficiency is approximately 43 percent greater for the V2G Pack than the Control Pack. Thus, not only is the "average" rate of decline of energy efficiency greater for the V2G Pack, but its decline is also accelerating more quickly than the Control Pack.

Technical Issues

As with most research projects, it is nearly impossible to predict all of the challenges that will arise through the course of a project. Several technical challenges resulted in testing gaps throughout the testing period where limited to no testing was performed. The following bullets document the technical issues encountered during the testing.

- The VIA battery systems were not put into full testing because performance issues prevented execution of the testing profiles. Prior to installation at UCSD, one of the battery packs had a failed balance board module. This pack was sent to VIA for repair.

Upon installation at UCSD, the other pack experienced an issue that eventually required it to be sent back to VIA and replaced. The replacement pack also had issues with the BMS SOC calibration. This troubleshooting required a significant level of effort to identify and attempt to resolve, but was ultimately unsuccessful.

- During testing at UCSD, communications disruptions occurred between the control system and the ABC-150 system. It was determined to be due to a conflict with a communication driver that enabled communications with the ABC-150 system. A manual work-around process was implemented to restart the software twice a week at the end of a test cycle to free the available memory and allow testing to continue uninterrupted. This resulted in partial test runs, which were accounted for during the analysis of the data.
- Several issues were noted from the end of July through October 2016 where the ABC-150 system would switch to local control mode in the middle of a test, halting the test. When this occurred, the battery pack had to be charged and balanced prior to restarting the test profile. A root cause for this occurrence could not be identified. In addition, during a maintenance event in September 2016, the negative leads to the battery packs were swapped. Although these negative lead connections are a common ground, this issue caused the ABC-150 system to enter a parallel mode at the start of a test until the batteries received a positive current command. To allow testing to continue as scheduled, the test profiles were modified to add a positive current command in second #1, which ensured they would execute. This did not affect the data validity, but did result in partial test files and the need to update the profile. After the root cause was identified, the negative leads were swapped back.

In summary, the intent to quantify degradation effects of V2G was successfully completed for the Valence battery systems. Despite the technical issues, these battery packs showed the degradation that was intended from this task.

Results and Discussion

Both driving and V2G activities (frequency regulation) were simulated in a controlled manner over time to gain a better understanding of potential V2G impacts on battery life. The standard test cycle was purposely more aggressive than expected PEV and V2G use to achieve significant battery degradation within the project period of performance.

Battery degradation factors were considered to obtain an understanding of the impact caused by each portion of the standard test cycle on each battery pack. The simulated drive cycle was more severe than the simulated V2G cycle based on the C-Rates of the cycle profiles and the rate of change of the power levels; however, total cycles, usage, DOD and temperature were more detrimental to the V2G Pack.

In the time domain, the capacity fade rate of the V2G Pack was greater than that of the Control Pack due to the added cycling represented by the V2G cycle and the V2G Packs higher mean operating temperature. However, in the total energy domain, the Control Pack had a higher rate of capacity fade.

Least-squared curve fits to the experimental data appeared to provide a good tool for predicting battery capacity fade for the 24-hour use cycles applied to each of the battery packs. For most of the battery performance measures investigated, a linear least-squared curve fit using battery temperature, time, and in some cases the second-order term of time, yielded relatively simple empirical equations to describe nearly all of the experimental variance observed. Coefficients on the time variable were useful to quantify the rate of degradation for the two battery packs.

While the statistical analysis provided good, and generally comprehensive, results, the values defined in this evaluation can only be properly used for similar battery usage as that represented by the drive and V2G cycles applied in this work. In a real-life scenario, variations in the total energy of a V2G cycle versus vehicle driving profiles are likely to yield different battery life reductions. In addition, other controllable factors such as temperature or float charge can also have an impact on battery degradation. Allowing a battery to cool between cycles and minimizing float charging have the potential to reduce the rate of battery degradation. To further quantify these effects, additional testing would be required.

For the conditions imposed in this assessment, over the course of the entire test period of over 600 days, the V2G Pack had capacity fade of 25 percent over nameplate, while the Control Pack had a capacity fade of 16 percent. Over the course of testing, total energy for the V2G Pack was 93.1 MWh, while 58.5 MWh passed through the Control Pack. An additional 34.6 MWh passed through the V2G Pack. Based on the testing of this project, the V2G Pack, experienced a 59 percent increase in total energy over the Control Pack. On a simplified total energy basis, the rate of degradation for both battery packs was nearly identical. However, when accounting for both operating temperature and second-order effects of time, the corrected rate of degradation was found to be less by approximately 19 percent for the V2G Pack relative to the Control Pack. Variations in the total energy represented by the V2G cycle versus that represented by other vehicle driving profiles are likely to yield different battery life reductions. Other controlling factors being comparable, the ratio of total V2G energy to that required for driving is likely to be a significant factor in determining actual battery life reduction for any potential V2G client.

Daily V2G operations do not cause significant degradation to PEV batteries beyond that experienced during drive cycles like those simulated in the project.

CHAPTER 4:
Modeling Simulation and Analysis

CTC used physical experimental data and numerical simulation results to quantify battery degradation based on different use scenarios. This effort focused on a comparison of simulated battery degradation, as modeled by software, and the measured degradation of battery packs based on laboratory testing performed from February 2015 through December 2016 at the CSE test facility, located in the UCSD Hopkins Parking Structure. The intent was to use available battery degradation modeling software to both compare V2G battery degradation test results with software-predicted outcomes and identify software that could accurately model V2G battery degradation and predict degradation based on specified usage profiles.

The following sections discuss the technical approach of the modeling simulation and analysis effort, including the software investigated and selected and profile construction in the selected software.

Simulation Tools Investigated

Three numerical simulation tools were investigated for use in battery life degradation modeling—the Second Life Battery Assessment software by Det Norske Veritas--Germanischer Lloyd (DNV-GL), second-life battery modeling by WMG Innovative Solutions of the University of Warrick and the Battery Lifetime Analysis and Simulation Tool (BLAST) by the National Renewable Energy Laboratory (NREL).

DNV-GL developed a software tool called Battery-XT that offered a platform to compare different battery technologies and evaluate their expected lifetimes relative to user-defined applications. The software considered a large number of interrelated factors including temperature, sizing, use profile, control system, as well as the chemistry and specific battery performance characteristics from participating manufacturers. It provided an economic assessment with payback periods for different second-use scenarios, recycling or other forms of reclaimable destruction of battery packs. Battery-XT had all the capabilities for detailed battery degradation modeling; however, this software was only available as a service; it was not available for third-party purchase. Compared to other options considered, subcontracting to DNV-GL was cost prohibitive and beyond the scope of this agreement.

WMG Innovative Solutions (WMG) of the University of Warrick, performed advanced research on battery chemistry, simulation, battery characterization and re-use/recycling. Discussions at the 2016 Battery Show Exhibition & Conference in Novi, Michigan included second-life battery modeling software developed by WMG. However, much like DNV-GL, they offered a service and not third-party purchase or use of their simulation software. Discussions with other vendors at the battery conference also yielded the same result; most battery degradation modeling was performed as a service due to the complexity of the associated software.

NREL's suite of public-domain BLAST software paired NREL's high-fidelity battery degradation model with a battery electrical and thermal performance model, application-specific electrical and thermal performance models of the larger system, application-specific system use data and historic climate data from cities across the United States. The software therefore had the potential to provide highly realistic long-term predictions of battery response and thereby enable quantitative comparisons of varied battery use strategies. The BLAST software suite included the following battery simulation models and tools:

- Behind-the-Meter Model – Employed simplified battery performance models for computational efficiency and an algorithm to create economically optimized energy storage solutions based on user-defined demand profiles.
- Battery Ownership Model – Determined electric vehicle costs by comparing the degradation rates and charging profiles of different batteries and factors in incentive programs to guide the user in constructing an ideal energy storage solution.
- BLAST-Vehicle (BLAST-V) – Focused on degradation of batteries in electric vehicle driving applications. A limitation of BLAST-V was the inability to load a user-defined custom profile, which was essential because of the custom V2G profile that would follow the daily driving profile in the current project.
- BLAST-Stationary (BLAST-S) Lite – Focused on simulating stationary battery pack degradation and allowed user-defined custom profiles and selection of geographical location for realistic temperature profiles to factor in environmental impacts on battery life. This software model was based on the lithium nickel cobalt aluminum (NCA) oxide ($LiNiCoAlO_2$) chemistry and was not available for other battery chemistries. (The chemistries used in the laboratory testing efforts were lithium iron phosphate and lithium iron magnesium phosphate.) All BLAST models were based on a MATLAB battery life model of a $LiNiCoAlO_2$ battery cell.

Simulation Tool Selected

The selected tool was BLAST-S Lite because it was the only tool investigated that allowed a user-defined input profile, a feature crucial to CTC’s analysis. BLAST-S Lite had 100 climate-location profiles available for modeling environmental temperature effects on battery health over time. The software predicted a variety of useful output figures such as an annual battery temperature plot, a 10-year cell-resistance growth curve and a 10-year capacity-fade curve. In addition, BLAST-S Lite allowed a 365-day user-defined power profile to be loaded so the user could capture seasonal variances in the analysis. With the 365-day power profile, the battery degradation over one year could be computed and the results forecasted for 10 years.

CTC understood at the outset of the simulation effort that the BLAST-S Lite was limited to the more common $LiNiCoAlO_2$ battery chemistry and intended for evaluating storage in stationary applications. CTC initiated the simulation effort using the existing BLAST-S chemistry with the assumption that the results would be useful in meeting project objectives. Again, updating the model with the correct battery chemistry was beyond the scope of this agreement.

Profile Construction

Running a non-standard power profile for battery degradation analysis required the generation of a comma-separated values (CSV) file according to a specific format to instruct the program. The CSV file could only have two columns of data: Column A defined the time steps and Column B defined the average power over the specified time step. Time steps did not have to be uniform in size; however, an exact 24-hour time span was required for each day (represented by a whole number of one), and any specific time needed to be represented by its decimal equivalent of a day (for example, 12:00 noon would be 0.5, while 3 a.m. would be 0.125). BLAST-S Lite expected a one-year-long profile composed of 365 days. The time column needed to begin at zero and end on 365. It was also important to scale the input power profile to the battery capacity expected by the program (BLAST-S Lite was modeled around a 22-kWh energy storage capacity) so the simulated battery and physically tested battery were discharged to the same SOC.

Another restriction while building power profiles was the inherent row quantity limitation for data entry within Microsoft Excel®. Assuming a consistent power profile in Excel, each day was restricted to 2,872 rows (data points), which could limit the fidelity of the profiles. However, because of the number of data points associated with the V2G profile (50,222), CTC generated profiles with millions of rows of data (exceeding Excel's inherent limitation of 1,048,576 rows) using a custom-written program to achieve the fidelity of the actual profile.

To meet BLAST-S Lite data input requirements, CTC averaged some portions of the power profiles exercised on batteries during laboratory testing. Two 24-hour power profiles were developed in Excel to imitate the physical testing performed on the two battery packs.

- The Control Pack profile consisted of three consecutive drive/charge cycles in series followed by a rest period at 100 percent SOC.
- The V2G Pack profile consisted of drive/charge cycles identical to the Control Pack profile, followed by a V2G cycle that was initiated when the SOC reached 50 percent during the third charge segment (after the third drive discharge). Fifty percent SOC enabled the battery to perform frequency regulation up or down (e.g., allowing the battery pack to be immediately discharged or charged).

The discharge duration of each drive cycle was 1.6 hours, followed by a charge cycle lasting 2.6 hours. The charge cycle consisted of an initial constant current charge (approximately 70 amperes (amps) per manufacturer's recommendation) until reaching the battery pack's voltage limits, then immediately transitioned to a constant-voltage charge until the battery reached 100 percent SOC. The majority of the constant-voltage charge was used to balance the battery cells. After completion of the 2.6-hour charge cycle, the profile began another drive cycle discharge and charge sequence. A total of three drive cycles per day defined the control conditions.

Table 23 shows the simulated amount of energy discharged in each profile and the energy used to recharge the battery either as a regenerative charge or recharge. The control profile portion of Table 23 shows the energy discharged, regenerated and recharged at the conclusion of the three drive cycles. The V2G profile shows the energy associated with the three drive cycles and V2G cycle, followed by the final charge. Due to the power lost to inefficiencies during the recharging process, the magnitude of the discharge values is less than those of the recharge values. Based on observations from test data, the recharge inefficiency was approximately 4–6 percent.

Table 23: Simulated Energy Cycling

	Control Profile	V2G Profile			
Battery State	3 Cycles	3 Drive Cycles	V2G Portion	Final Charge	Units
Discharging	-49.79	-49.79	-32.12	0	kWh
Regeneration	0.67	0.66	0	0	kWh
Charge	52.71	* 41.14	26.75	17.89	kWh

*** V2G event begins at 50 percent SOC, requiring less charge than the control profile.**

Source: Concurrent Technologies Corporation

The V2G portion of the standard test profile began during the charge phase immediately following the third drive cycle when the SOC reached 50 percent (actual testing had a 2.2-hour rest). The oscillating charging and discharging of the V2G profile lasted 9.3 hours. This represented a simulated California Independent System Operator automatic generation control signal in the frequency response auxiliary market. Adding the V2G cycling after the three drive cycles resulted in a substantial cycle time increase for a total of 20.6 hours of cycling per day including all charging to bring the battery SOC back to 100 percent. See Table 24 and Table 25 for greater detail on profile structures.

The drive discharge segment contained the instantaneous energy demand (watt-seconds) for a battery undergoing an urban driving route. The original (high fidelity) drive profile represented 1.56 hours of battery use (5,630 data points) with an average speed of 19.6 miles per hour and a maximum speed of 56.7 miles per hour. The V2G profile evaluated by the simulation software contained the instantaneous energy demand (watt-seconds) of a battery experiencing the most aggressive periods of the Regulation Energy Management (REM) Duty Cycle again scaled to the limitations of the battery. Using the REM profile, the segments with the maximum signal frequency, energy transfer and overall duty were selected and merged into a custom V2G power demand profile containing 33,313 data points defining 9.25 hours of cycling. Notice that Table 24 also defines the number of data points associated with high- and low-profile fidelity and the SOC at the end of each profile segment. Table 25 contains the same information for the V2G profile with the exception that only low-fidelity data were considered because it exceeded the limitation of Excel, which is 1,048,576 rows of data.

Table 24: Control Pack One-Day Profile

Profile	Segment	Data Points		Duration (hours)	End SOC (percent)	Notes
		High Fidelity	Low Fidelity			
Control Profile	**Drive Discharge 1**	5,630	901	1.56	26	Urban driving profile
	Constant Current Charge	1	1	1.36	99	Constant current charging
	Constant Voltage Charge	5	2	0.95	100	Constant voltage cell balancing
	Drive Discharge 2	5,630	901	1.56	26	Urban driving profile
	Constant Current Charge	1	1	1.36	99	Constant current charging
	Constant Voltage Charge	5	2	0.95	100	Constant voltage cell balancing
	Drive Discharge 3	5,630	900	1.56	26	Urban driving profile
	Constant Current Charge	1	1	1.36	99	Constant current charging
	Constant Voltage Charge	5	2	0.95	100	Constant voltage cell balancing
	Rest	1	1	12.37	100	Rest period after cell balancing
		16,909	2,712	24 hours		

Source: Concurrent Technologies Corporation

Table 25: V2G Pack One-Day Profile

Profile	Segment	Data Points	Duration (hours)	Ending SOC (percent)	Notes
V2G Profile	**Drive Discharge 1**	5,630	1.56	26	Urban driving profile
	Constant Current Charge	1	1.36	99	Constant current charging
	Constant Voltage Charge	5	0.95	100	Constant voltage cell balancing
	Drive Discharge 2	5,630	1.56	26	Urban driving profile
	Constant Current Charge	1	1.36	99	Constant current charging
	Constant Voltage Charge	5	0.95	100	Constant voltage cell balancing
	Drive Discharge 3	5,630	1.56	26	Urban driving profile
	Constant Current Charge	1	0.47	50	Constant current charging
	Vehicle to Grid Cycling	33,313	9.25	25	V2G Cycling
	Constant Current Charge	1	1.33	99	Constant current charging
	Constant Voltage Charge	4	0.23	100	Constant voltage cell balancing
	Rest	1	3.39	100	Rest period after cell balancing
		50,222	24 hours		

Source: Concurrent Technologies Corporation

Software Analysis

The battery degradation observed in controlled physical testing was significantly greater than the degradation predicted by BLAST-S Lite. This was likely a result of differences between a simulating a drive profile versus a stationary application. Table 26 shows the actual and predicted values for remaining storage capacity of the battery packs and the number of cycles executed. The storage capacity of the actual batteries was determined by how much energy (in watts-hours) could be discharged from each fully charged battery pack at the beginning and end of testing.

Table 26: Results Summary

Profile	Source	Remaining Storage Capacity Estimate (percent)	Number of Drive and V2G Events	Calendar Days
Control (3 drive cycles)	**Experimental**	84	1,497	499
	BLAST Low Fidelity†	94	1,500	500
	BLAST High Fidelity†	96	1,500	500
V2G (3 drive cycles + V2G cycle)	**Experimental**	75	1,960	490
	BLAST High Fidelity†	96	2,000	500

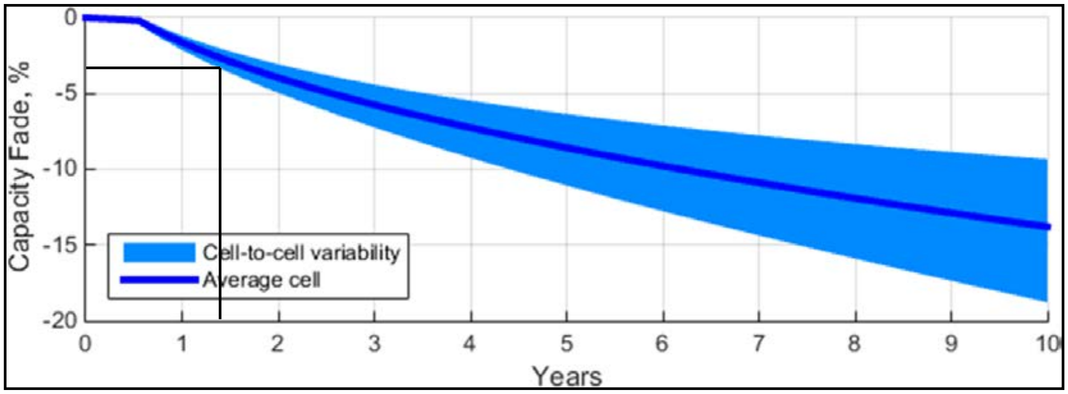
† Estimate from BLAST capacity fade curve

Source: Concurrent Technologies Corporation

To summarize the results, BLAST-S Lite degradation predictions were substantially less than the degradation measured from testing actual batteries. When more fidelity (data) was added to the model, the estimated capacity fade substantially decreased. This contradicted what one might expect and is discussed in more detail below.

Figure 44 shows that BLAST-S Lite predicted the battery capacity for the high-fidelity V2G power profile would fade by approximately 4 percent in 500 days of use. The physical testing demonstrated 25 percent capacity fade in a similar number of days of use. The large discrepancies between the physical tests and the simulations for both battery sets indicated significant issues with the simulation results. While much of the discrepancy was likely due to dissimilar battery chemistries and simulation basis (driving versus stationary application) between the physical tests and the simulation, CTC did not rule out other causes for the poor agreement. It should be noted that NREL BLAST tools are complex and require additional collaboration that was beyond the scope of this agreement. While capacity fade differences between the high- and low-fidelity results for the Control Pack could be explained as due to differences in model refinement, the differences between the Control and V2G Packs were not easily explained. Due to the extra cycling associated with the V2G cycles, the V2G Pack must have a higher amount of capacity fade; this was clearly observed in the physical test results. However, the simulation results showed less capacity fade for the V2G Pack than for the Control Pack during 500 days of simulated use.

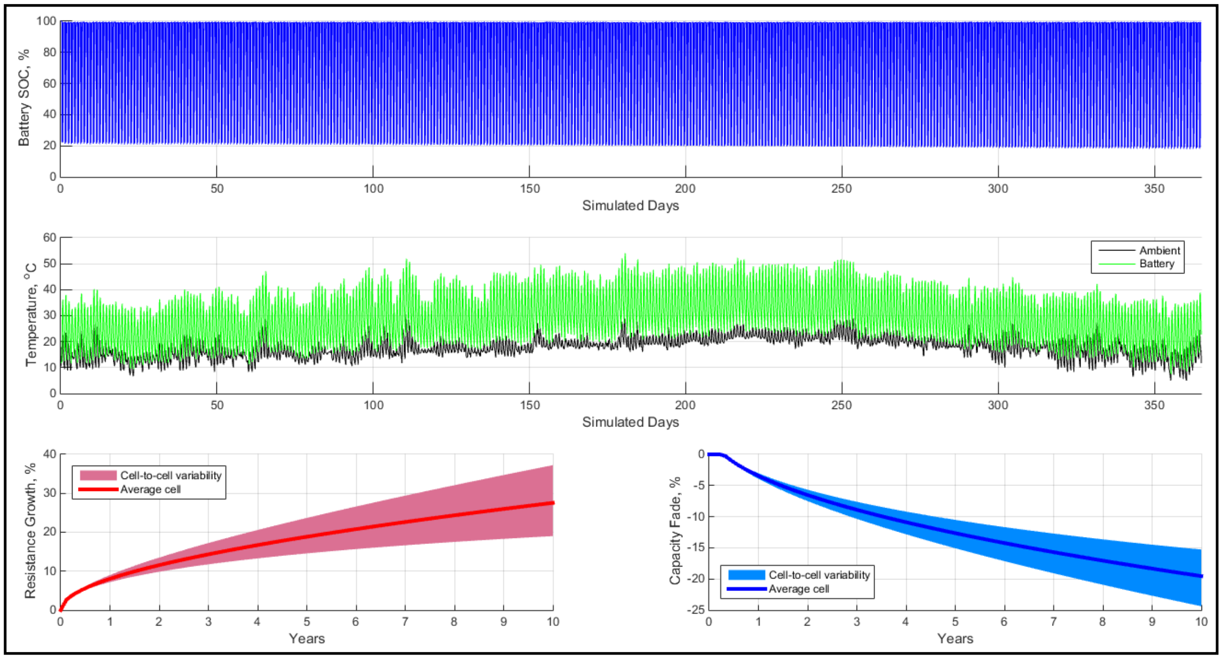
Figure 44: BLAST-S Capacity Fade Curve for V2G Profile (High-Fidelity)



Source: Concurrent Technologies Corporation

After seeing such large discrepancies in BLAST-S Lite predictions of capacity fade, earlier developmental profiles of lower fidelity (fewer data points) were re-examined. Figure 45 shows the BLAST-S Lite simulation output of the low-fidelity control profile with three cycles per day captured in 2,712 rows of data per day. Compare the battery SOC curve at the top of Figure 45 with that of Figure 46; the SOC oscillates between approximately 100 and 20 percent throughout the duration of the simulation in both profiles but the density of the oscillations in Figure 46 is greater due to increased fidelity. At 500 days, with three drive cycles per day, the capacity degradation is approximately 7.0 percent, which is roughly 235 cycles per one percent capacity fade. For ease of comparison, capacity loss is described as cycles per one percent capacity fade throughout this section.

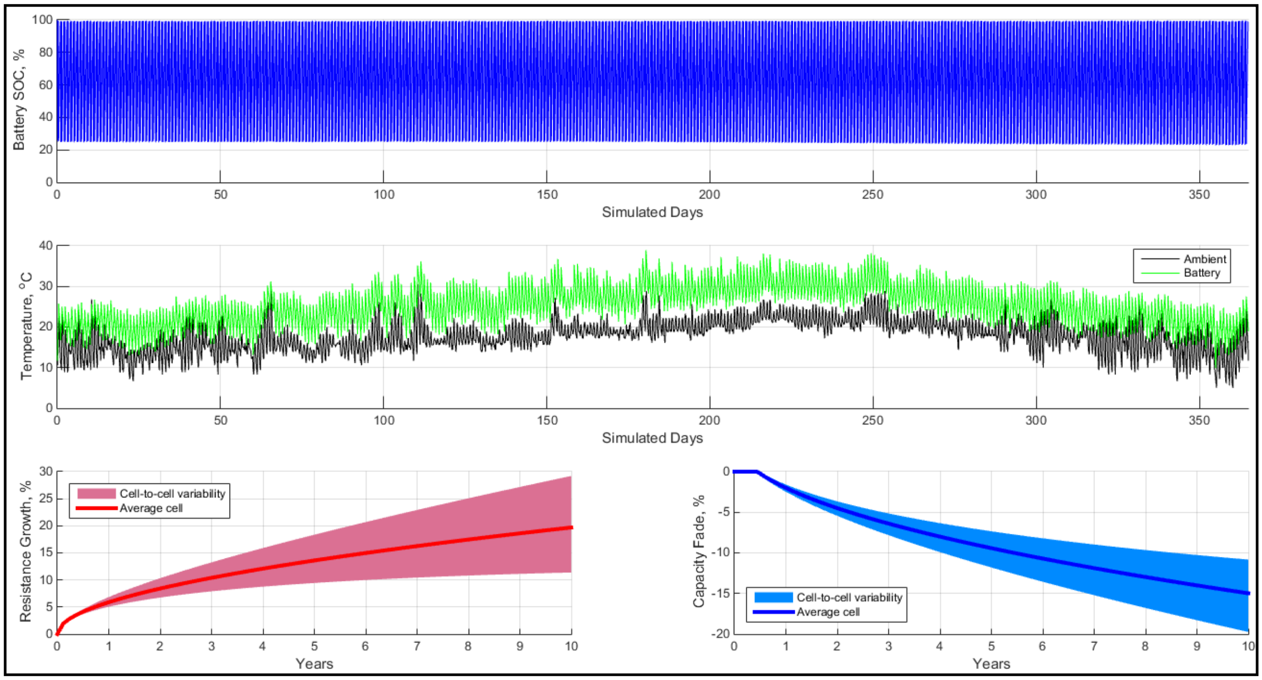
Figure 45: Control Pack Profile (low-fidelity)



Source: Concurrent Technologies Corporation

Figure 46 shows the BLAST-S Lite simulation output of the control profile with three drive cycles per day captured in 16,909 rows of data per day. At 500 days, with three drive cycles per day, the capacity fade was approximately 4.0 percent, which was roughly 410 cycles per one percent capacity fade.

Figure 46: Control Pack Profile (high-fidelity)

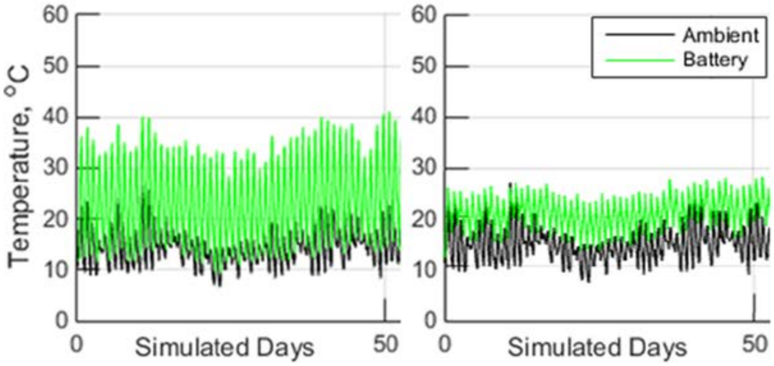


Source: Concurrent Technologies Corporation

Comparing the capacity fade of the low-fidelity Control Pack profile simulation (235 cycles per one percent capacity fade) with that of the high-fidelity profile simulation (410 cycles per one percent capacity fade), a difference of approximately 54 percent can be seen. In other words, refining the time step by a factor of 6.2 affected the output by 54 percent. Such large differences occur in other numerical analysis software applications (such as finite element analysis codes) when differences in discretization size (time steps, element size or material properties) yield one of two contrasting situations. On one hand, when the discretization is too coarse, phenomena of a lower size are not correctly captured. On the other hand, when the discretization is too fine, numerical errors occur when subtracting nearly equal values or when values of widely different magnitudes are summed. Both extremes lead to significant, and typically unacceptable, errors. CTC suspected, but could not confirm, that a discretization effect contributed to the poor agreement between the low- and high-fidelity Control Pack results.

Figure 47shows a small segment of the battery and ambient temperature profile for both the low- and high-fidelity models. The general trends over time in the battery temperature are similar, but the magnitudes of the predicted temperatures are very different. The low-fidelity temperature plot is shown on the left and has several maximum temperature peaks (green line) around 40 °C. Contrast that with the temperatures from the high-fidelity temperature plot shown on the right, whose temperatures peak around 28 °C. Assuming an average ambient temperature of 18 °C in San Diego, California, where laboratory testing occurred, the predicted temperature increase in the battery over the ambient temperature (i.e., the difference between the battery and ambient temperatures) for the low-fidelity results is approximately 22 °C, while that for the high-fidelity results is approximately 10 °C. This temperature discrepancy likely accounts for some of the differences in predicted capacity fade as discussed above. This large difference in battery temperatures is further evidence of a discretization issue, as discussed above, or other serious issue with the current application of the software.

Figure 47: Temperature Profile Segment Comparison



50-Day Temperature Profile (low fidelity—left / high fidelity—right)
Source: Concurrent Technologies Corporation

Results and Discussion

The inability to predict battery degradation that was shown in the laboratory testing is based on several factors that could be addressed in future work. BLAST-S was design for stationary battery applications and based on $LiNiCoAlO_2$ battery chemistry. A combination of BLAST-V and BLAST-S may have predicted the degradation that was seen in the laboratory testing, however this was beyond the scope of this agreement. The load on an electric vehicle's battery fluctuates rapidly from second to second with the potential of full power demand for a few seconds, then an immediate transition to a brief regenerative charge, then back to full demand, then a rest. This highly dynamic cycling is common in EV applications, but less likely for a stationary battery application.

Additionally, large data sets with large power fluctuations experienced by the physical batteries during laboratory testing may have not been interpreted as expected. Table 27 shows what appears to be a relationship between profile fidelity (additional load fluctuations) and predictions of decreasing degradation. This table shows that increased profile fluctuations (via additional data points) results in reduced battery degradation. Notice that the addition of the V2G cycles adds 33,313 data points and reduces the degradation by 1.5 percent. One interpretation of the added V2G data is that the profile is less aggressive than the drive cycle. An alternative interpretation is that BLAST-S Lite may have been overwhelmed by the quantity of data provided by the high-fidelity profiles.

Table 27: Single-Day Profile Fidelity

Cycling Events	Fidelity	Data Points	1.5-Year Degradation (percent)
3 Drive Cycles	Low	2,712	7
3 Drive Cycles	High	16,909	4
3 Drive Cycles + V2G	High	50,222	3

Source: Concurrent Technologies Corporation

The BLAST-S Lite tool has all the input selections necessary to enable the average user to configure the simulation parameters (location-based climate data, battery cooling and custom load profile) to their specific needs—all while being available to the public at no cost. Furthermore, the software is simple enough for an inquisitive user to learn while providing meaningful results such as battery temperature fluctuation throughout the year and a capacity fade curve. Although CTC was unable to generate degradation simulation results similar to those measured during physical testing, BLAST-S Lite has the potential to meet the average user's needs to explore battery degradation effects of custom battery use profiles. Current accuracy of the software remains unknown to CTC as a result of inadequate understanding of the effects of assumptions made by CTC in its use and CTC's application of the software. CTC suggests future users engage with NREL to ensure complete understanding of how to use the software.

CHAPTER 5: Second-Life Battery Applications

Vehicle batteries become impracticable for efficient electric driving when aging causes a battery to lose approximately 20 percent of its energy storage capacity. Capacity loss or capacity fading is a phenomenon observed during use of rechargeable batteries. The "battery life time cost" is the total cost of the battery when distributed over the life cycle of the vehicle. Used batteries can be reused in applications where the requisite performance parameters—particularly the remaining energy density (e.g., watt-hours per kilogram)—are not as demanding as in EV applications. An example of reusing EV batteries is grid-connected applications (i.e., peak-shaving, power quality or renewable integration).

A peer-reviewed Mineta National Transit Research Consortium report titled "Remanufacturing, Repurposing, and Recycling of Post-Vehicle-Application Lithium-Ion Batteries"[9] suggests three reasonable second-life uses for expended automotive lithium-ion batteries:

- Remanufacturing for reuse in vehicles by replacing any damaged cells
- Repurposing by reengineering battery for stationary storage application
- Recycling by disassembling each battery cell and extracting the metals, chemicals and other byproducts to be sold or re-introduced into the battery manufacturing process.

Post-vehicle applications for lithium-ion batteries will become increasingly important in the coming years as the batteries supplied with the first modern-day mass-produced electric vehicles degrade to the point that they are unsuitable for automotive use. The focus of this task was to enable PEV batteries to be repurposed for large-scale, stationary storage applications for California utilities.

The following sections discuss the technical approach of the second-life battery application design effort, which included the following key elements:

- Examined potential applications and benefits of second-life batteries
- Documented key challenges for deploying grid-level energy storage and the critical factors that impact the economic viability of second-life battery applications such as reuse and recycling of the used batteries
- Developed a second-life requirements document to guide the packaging of PEV second-life batteries for use as stationary energy resources
- Prepared a preliminary design concept for second-life battery applications based on the technical requirements document

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[9] http://transweb.sjsu.edu/PDFs/research/1137-post-vehicle-Li-Ion-recycling.pdf (June 2014)

- Developed a determination of condition (DoC) diagnostic protocol, evaluated recent Underwriters Laboratory Inc. (UL) work on a complementary standard, and performed laboratory module testing to validate the proposed protocol.

Potential Applications/Benefits

A significant level of interest has been expressed in repurposing vehicle traction batteries over the past several years. Applications from residential single-battery packs to large-scale, multi-pack grid storage applications have been considered and demonstrated. The application of interest will drive the energy storage power and energy requirements design to match grid-scale needs. Applications such as time of use management and peak shaving will typically be driven by more energy-intense requirements than a power driven need where capacity firming and frequency regulation are applied.

Sandia National Laboratories performed a study and authored a report entitled "Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide."[10] Their goal was to evaluate market areas, their requirements and business potential for utility business opportunities through use of stationary energy storage applications for economic advantages. Table 28, as outlined in this report, provides the key results of their study. This table contains five criteria for the 17 primary benefit types characterized in the Sandia report.

- Discharge duration indicates the amount of time the storage device must discharge at its rated output before charging is required.
- Capacity indicates the power rating range of a storage system that apply for a given benefit.
- Benefit details the present worth of the respective benefit type over a 10-year period considering 2.5 percent inflation and a 10 percent discount rate.
- Potential lists the maximum market potential for the respective benefit type over 10 years in California and the United States.
- Economy reflects the total value of the benefit given the maximum market potential.

This study provides a starting point for bounding the size of an energy storage system using second-life batteries.

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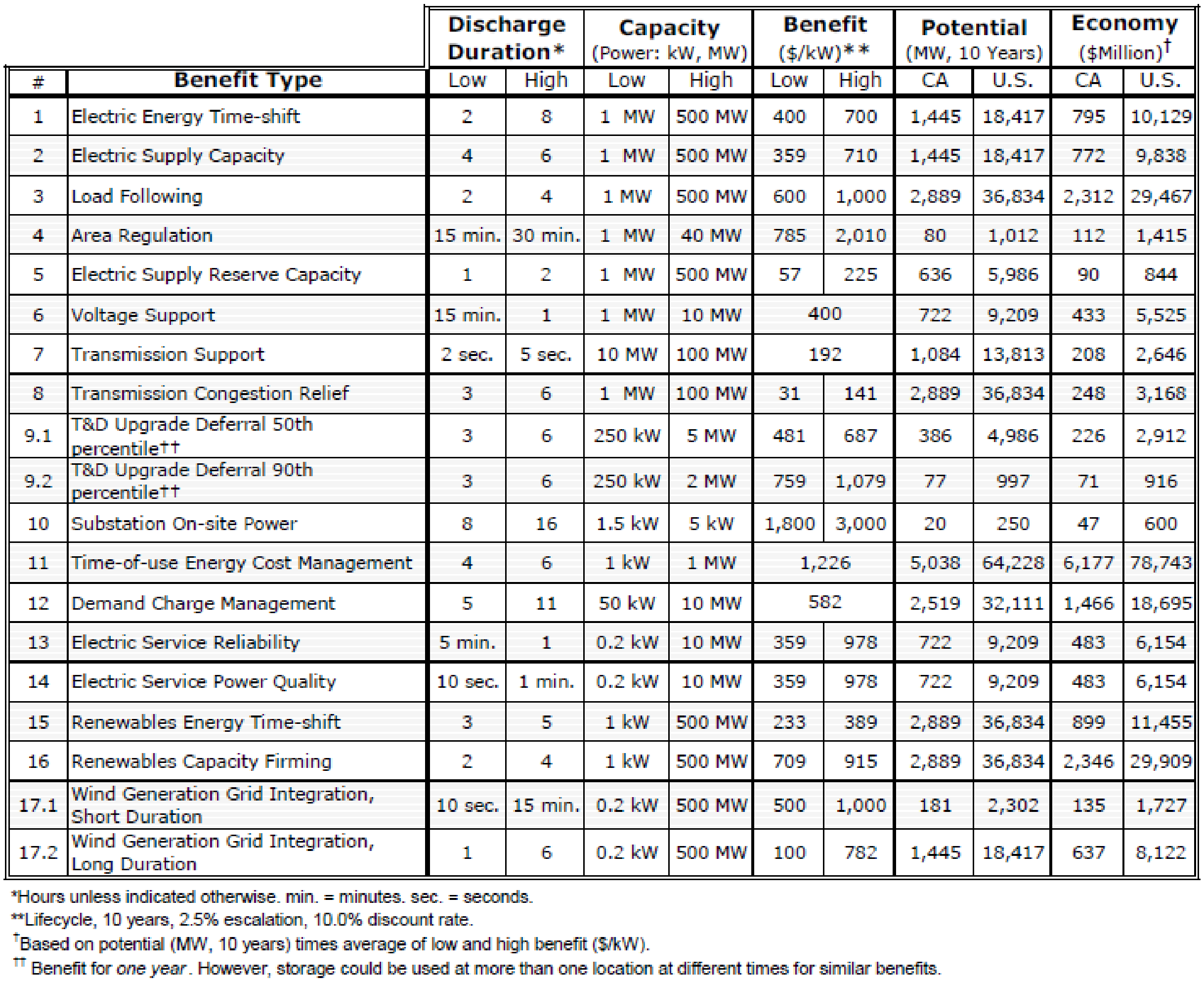
[10] 5 http://www.sandia.gov/ess/publications/SAND2010-0815.pdf (February 2010)

Table 28: Sandia National Laboratories Study Results



#	Benefit Type	Discharge Duration*		Capacity (Power: kW, MW)		Benefit ($/kW)**		Potential (MW, 10 Years)		Economy ($Million)†	
		Low	High	Low	High	Low	High	CA	U.S.	CA	U.S.
1	Electric Energy Time-shift	2	8	1 MW	500 MW	400	700	1,445	18,417	795	10,129
2	Electric Supply Capacity	4	6	1 MW	500 MW	359	710	1,445	18,417	772	9,838
3	Load Following	2	4	1 MW	500 MW	600	1,000	2,889	36,834	2,312	29,467
4	Area Regulation	15 min.	30 min.	1 MW	40 MW	785	2,010	80	1,012	112	1,415
5	Electric Supply Reserve Capacity	1	2	1 MW	500 MW	57	225	636	5,986	90	844
6	Voltage Support	15 min.	1	1 MW	10 MW	400		722	9,209	433	5,525
7	Transmission Support	2 sec.	5 sec.	10 MW	100 MW	192		1,084	13,813	208	2,646
8	Transmission Congestion Relief	3	6	1 MW	100 MW	31	141	2,889	36,834	248	3,168
9.1	T&D Upgrade Deferral 50th percentile††	3	6	250 kW	5 MW	481	687	386	4,986	226	2,912
9.2	T&D Upgrade Deferral 90th percentile††	3	6	250 kW	2 MW	759	1,079	77	997	71	916
10	Substation On-site Power	8	16	1.5 kW	5 kW	1,800	3,000	20	250	47	600
11	Time-of-use Energy Cost Management	4	6	1 kW	1 MW	1,226		5,038	64,228	6,177	78,743
12	Demand Charge Management	5	11	50 kW	10 MW	582		2,519	32,111	1,466	18,695
13	Electric Service Reliability	5 min.	1	0.2 kW	10 MW	359	978	722	9,209	483	6,154
14	Electric Service Power Quality	10 sec.	1 min.	0.2 kW	10 MW	359	978	722	9,209	483	6,154
15	Renewables Energy Time-shift	3	5	1 kW	500 MW	233	389	2,889	36,834	899	11,455
16	Renewables Capacity Firming	2	4	1 kW	500 MW	709	915	2,889	36,834	2,346	29,909
17.1	Wind Generation Grid Integration, Short Duration	10 sec.	15 min.	0.2 kW	500 MW	500	1,000	181	2,302	135	1,727
17.2	Wind Generation Grid Integration, Long Duration	1	6	0.2 kW	500 MW	100	782	1,445	18,417	637	8,122

*Hours unless indicated otherwise. min. = minutes. sec. = seconds.

**Lifecycle, 10 years, 2.5% escalation, 10.0% discount rate.

†Based on potential (MW, 10 years) times average of low and high benefit ($/kW).

†† Benefit for *one year*. However, storage could be used at more than one location at different times for similar benefits.

Source: Table ES-1 from The Sandia Report - Energy Storage for the Electricity Grid: Benefits & Market Potential Assessment Guide (Feb. 2010)[11]

Second-life battery packs have the potential to meet many of the applications (benefit type) listed above.

Energy Storage Challenges

In a 2013 Grid Energy Storage report[12], the Department of Energy (DOE) suggests that not every type of storage is suitable for every type of application, demonstrating the need for a portfolio strategy for energy storage technologies. In this same report, the DOE identified four challenges

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[11] http://www.sandia.gov/ess/publications/SAND2010-0815.pdf (February 2010)

[12] Grid Energy Storage, December 2013, http://energy.gov/sites/prod/files/2014/09/f18/Grid%20Energy%20Storage%20December%202013.pdf

to the widespread deployment of energy storage; addressing these challenges will be key to deploying second-life battery solutions. These four challenges include:

1. Cost competitive energy storage technologies (including manufacturing and grid integration)
2. Validated reliable and safe operations
3. Equitable regulatory environment
4. Industry acceptance.

Understanding these challenges and addressing them in an energy storage system (ESS) design in a cost effective manner will be critical for industry to adopt and deploy second-life battery systems as a viable grid-level energy storage solution.

Factors Impacting Economics for Second-Life Uses

Lithium-ion batteries used in PEVs must be disposed, recycled or reused at some point during the vehicle life. Significant quantities (> 1 GWh) of these batteries are expected to require disposition starting in 2025, fifteen years after the first commercial PEVs started being sold in North America in any substantial quantity. Peak shaving is often accomplished by energy storage technologies and provides a large market where PEV batteries could be repurposed with a second-life. However, to economically compete with the alternative of newly built batteries, repurposing costs must be kept to a minimum.

The following sections address several factors that could impact the economics for second-life use.

Delaying Recycling Through Repurposing

The cost of recycling must be considered in the economics of lithium-ion batteries use in vehicle power. Few overarching U.S. laws and regulations govern battery recycling. The Mercury-Containing and Rechargeable Battery Management Act of 1996 sets forth requirements regarding the disposal of batteries from PEVs, but its scope is limited and excludes lithium-ion batteries. Second, the Electric Vehicle Deployment Act of 2010 merely directs the Secretary of Energy to carry out a study on recycling materials from EV batteries. Because of relatively high recycling costs and uncertain regulations, there is no clear path to economically recycle lithium-ion batteries.[13]

Presently, recycling lithium-ion batteries is not profitable and will likely lead to increased waste from discarded, used batteries. Consequently, the importance of maximizing the economic and environmental value before the battery’s primary life ends is critical to successfully repurposing batteries for second-life applications. To date, no facility exists in the United States for lithium-ion battery recycling. Only one facility, Retriev Technologies (formerly Toxco) in Ohio, plans to begin recycling lithium-ion batteries. The plant currently processes lead acid and nickel metal hydride batteries used in the current generation of hybrid EVs. Pursuant to a $9.5 million grant

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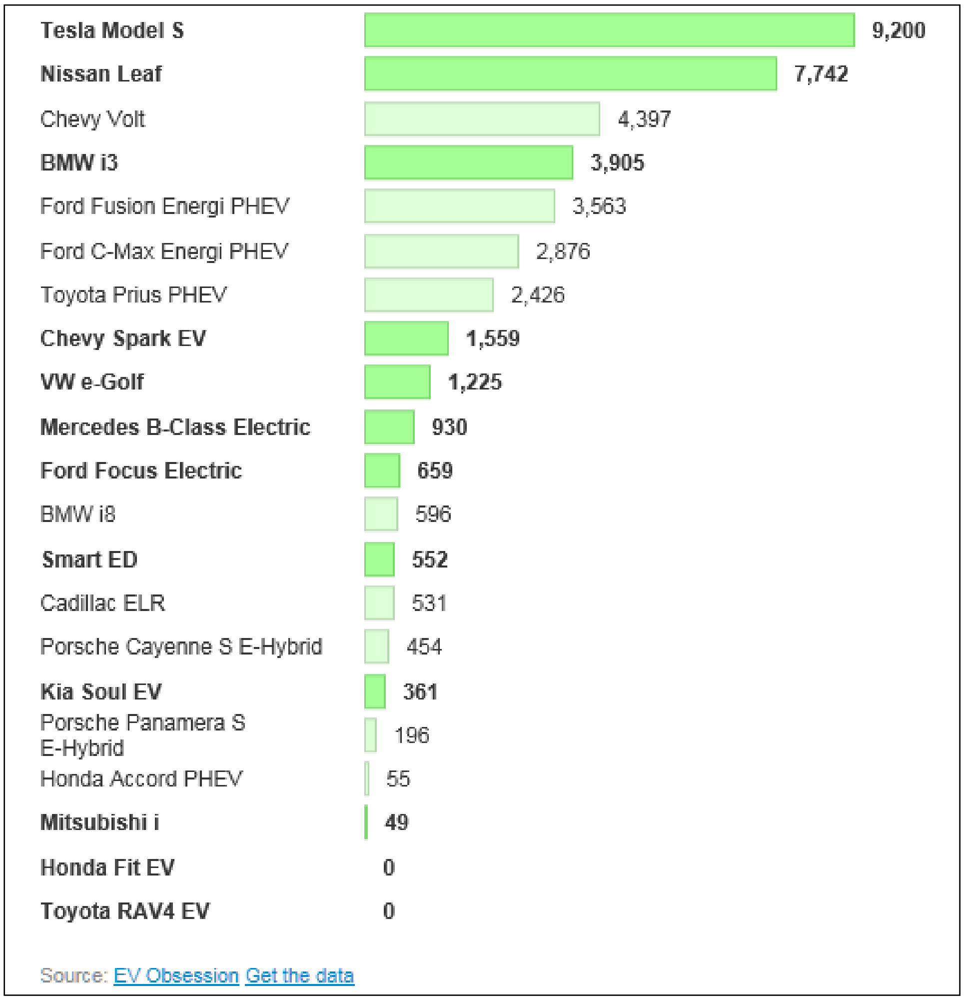
[13] https://www.law.berkeley.edu/files/ccelp/Reuse_and_Repower_--_Web_Copy.pdf

from the U.S. DOE, it will soon expand to allow for the processing of more advanced (large-format) lithium-ion batteries from EVs. The process will involve separating the battery components and recycling the materials to recover battery-ready materials, including nickel, cobalt, copper, lithium and other metals from cell and module enclosures.[14]

Availability of PEV Batteries

Figure 48 shows the PEV car sales in the United States for year to date through May 2015. Per DMV.com, California leads the US in PEV sales.[15] From the data, Tesla Model S had the most PEV sales followed by the Nissan LEAF and then the Chevy Volt. Consequently, the majority of batteries available for second-life research and development will come from these vehicles.

Figure 48: US PEV YTD 2015 Car Sales



Source: EV Obsession Get the data

Source: Concurrent Technologies Corporation

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[14] https://www.law.berkeley.edu/files/ccelp/Reuse_and_Repower_--_Web_Copy.pdf

[15] https://www.dmv.com/blog/California-leads-the-country-in-EV-sales-521251

In February 2015, the National Renewable Energy Laboratory (NREL) published a report, "Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries"[16], which detailed the feasibility of, and major barriers to, the second-life use of modern lithium-ion PEV batteries. This report will be hereafter referred to as "NREL/TP-5400-63332 Report."

The NREL/TP-5400-63332 Report documents a detailed analysis of battery degradation in automotive service and the economics of battery replacement, concluding there is little economic incentive or technical requirement to replace a PEV battery prior to the end of the original vehicle's service life. Consequently, the standard 15-year service life for vehicles is assumed to be the duration before a PEV's battery is available for second-life applications. However, it is worthy to note the Nissan LEAF and Chevy Volt have an 8-year/100,000 mile warranty, which includes battery replacement.[17]

Based on calculations for potential battery-damaging accidents, the NREL/TP-5400-63332 Report estimates 80 to 90 percent of PEV batteries will be in usable condition at the end of a 15-year service life.

The number of PEV batteries to be disposed, recycled or become available for second-life usage can be expected to rise at approximately the same rate as the increase of PEVs (~20 percent per year), but with a 15-year delay. Therefore, batteries for second-life usage will become widely available in approximately 2025; 15 years after the Chevrolet Volt and Nissan LEAF began North American sales. By these estimates, this would provide a market availability of approximately 45,000 PEV batteries for second-life usage across the entire United States in the year 2027, with availability rising rapidly in the following years. In the early years, 40 percent of the available PEV batteries are estimated to be in California due to state electric car subsidies.

Capacity of Second-Life PEV Batteries

The NREL/TP-5400-63332 Report uses data for PEVs sold in California from December 2010 to June 2014 and calculates the average installed energy capacity to be 22.3 kWh per vehicle. This average will increase or decrease depending upon which vehicle type, PHEVs or all-electric vehicles, will come to dominate the market. As PHEVs utilize a gasoline engine, they often use smaller batteries (typically less than 20 kWh) while PEVs seek to maximize battery capacity to boost vehicle range and use larger batteries (24–36 kWh).

For its baseline second use repurposing calculations, the NREL/TP-5400-63332 Report assumed a regional collection case with 600,000 kWh (per year of battery throughput). This corresponds to approximately 25,000 PEV batteries per year, not far from the assumed battery availability for the first few years in California.

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[16] http://www.nrel.gov/docs/fy15osti/63332.pdf

[17] http://driveclean.ca.gov/pev/Dispelling_Myths.php

A 22-kWh battery may have a considerably lower capacity at the end of a 15-year service life. Numerous factors including driving patterns, climate and whether the battery was used in a PEV or PHEV, will determine the final capacity at the end of 15 years of use. The assumption is that, at the end of a 15-year vehicle service life, the battery will have approximately 70 percent of its initial depth of discharge (DOD) remaining when made available for a second use.

The NREL/TP-5400-63332 Report notes a battery that has lost 30 percent of its initial capacity cannot cycle at greater than a 70 percent DOD. Further, if this battery were cycled at 70 percent DOD, it would be able to deliver this capacity a very limited amount of times as the battery continues to age and degrade. These batteries will likely have served 15 years in an automobile and are unlikely to have been designed to substantially exceed the vehicle's lifetime. Therefore, other mechanisms not accounted for in the present battery degradation model (NREL's Battery Ownership Model and BLAST-V tool) (e.g., corrosion, failure of cell seals, fatigue of electrical connections, long-term electrochemical effects not yet witnessed in the underlying data) may become the primary pack failure mode if the second use lifetime becomes too large. For these reasons, the NREL/TP-5400-63332 Report limited its assumptions to 50 percent and 60 percent DOD scenarios and a maximum 10-year second-use battery life. For some scenarios, 10 years may be too optimistic, and the second-life service may be as little as 3 years.

Battery Performance Data

Battery performance data can spur – or limit – the market. Vehicle developers are not likely to share battery performance data, making it harder for other entities to predict battery performance for second-life usage. Participants in a study conducted by Emmett Institute on Climate Change and the Environment at the University of Los Angeles California School of Law, Center for Law, Energy & the Environment (CLEE) Berkeley Law, noted a lack of data on second-life batteries due to uncertainty about how the batteries were performing in their "first life" role as mobile energy storage devices. Potential customers for second-life batteries, therefore, lack knowledge about how the batteries performed in the first instance and under what conditions, as well as how much capacity remains in them. Adding to this uncertainty is lack of knowledge of how these batteries will respond when used in innovative and sometimes unanticipated ways.[18]

Potential Cost

Second-life battery use could be at considerable technical disadvantage compared to utilizing new batteries custom built for stationary energy applications. New batteries will have a much higher energy density than second-life batteries, both because of second-life degradation and because they will be built on 15-year-old technology, without the accompanying improvement over time in battery efficiency. They will also have a reduced service life compared to new batteries.

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[18] https://www.law.berkeley.edu/files/ccelp/Reuse_and_Repower_--_Web_Copy.pdf

The NREL/TP-5400-63332 Report estimates that new battery packs could cost $250/kWh by 2020 and $150/kWh by 2030. To compete on economic grounds, second-life PEV batteries must be available at a low enough cost to compensate for their performance disadvantages.

The used-battery buying price paid to the automotive battery owner (the salvage value) remains an unknown. Potentially this cost could be $0 or a negative number in a "pay to take" situation where the battery owner must dispose of the battery and all methods have associated costs. However, if the sale of second-life battery energy storage systems is profitable, it is likely that market forces would drive the salvage value of used vehicle batteries back to a positive value.

What can be calculated is the repurposing cost, which is the cost involved in the processes between retiring a battery from automotive service and selling it to a secondary market. These are discussed in detail in the NREL/TP-5400-63332 Report, along with requirements for minimizing repurposing costs.

It suggests that PEV battery second-life has little ability to reduce the upfront cost of PEVs, but it can eliminate end-of-service costs for the automotive battery owner and provide low- to zero-emission peaking services to electric utilities, reducing cost, use of fossil fuels and greenhouse gas emissions.

Liabilities Concerns

Potential liabilities issues related to second-life use of vehicle batteries include questions related to responsibilities for safety and disposal. These issues will need to be addressed as these batteries become available for second-use applications.

When a battery has a defect or is linked to damages to people or property, the owner is generally liable for some portion, if not all costs for retribution. If a battery malfunctions during the first-life vehicle application, the manufacturer may be responsible for its performance. However, when an electric vehicle manufacturer makes a battery and ensures it for use in typical, foreseeable automotive uses, that manufacturer does not necessarily anticipate that the vehicle owner will sell or give the used battery to another party for uses in creative ways to serve the grid or other customer needs. Automotive manufacturers that provide the original battery may want to discourage or limit secondary uses to avoid liability. Core charges or a charge to ensure the used battery is returned are a likely approach that could be employed.

Currently, regulations and standards regarding liability for second-life batteries are unclear and may discourage automakers from allowing their batteries to be used outside of the vehicle, other than for recycling. Recycling of lead-acid batteries is successful in part due to the following.

- Disposal is illegal in most states; most states have regulations covering the disposal of vehicle lead acid batteries.
- Many states require a monetary deposit as an incentive for consumers to return their batteries.

- Most lead-acid batteries are collected when new ones are purchased. The dealers are required to accept them and are paid for the collection. In some cases, used batteries can be returned to the manufacturer for recycling[19]

Adapting these regulations/practices for lithium-ion batteries may actually discourage the second-life use.

Potential Up Side

As with any new technology, there are many unknowns and questions regarding the potential of the technology to achieve a value proposition. In an effort to reduce uncertainty and cost, it is recommended that continued support be provided to demonstrate second-life battery research projects. This research provides useful data moving technologies through the development process. To date, small-scale pilots have been conducted with specific battery technologies, but multiple batteries grouped to meet an ESS objective have not been tested. Overall EV battery performance data in vehicle-to-grid applications will assist the Energy Commission in determining value for individual and integrated systems as well as quantify the potential impacts to the electric grid.

Based on the NREL/TP-5400-63332 Report, NREL has identified grid-connected combustion turbine peaker plants as a promising application for second use batteries. Looking at the market potential, another application of interest would be frequency regulation. This will be a challenging application for these batteries; however, it has the potential to provide a large economic benefit to groups deploying energy storage.

As discussed above, the Sandia National Laboratories study entitled “Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide” evaluated market areas, requirements and business potential for utility business opportunities through use of stationary energy storage applications for economic advantages. Second-life battery packs integrated to meet ESS design requirements have the potential to meet many of the applications (benefit type) listed in Table 28, such as load following, time of use energy management, demand charge management and renewables capacity firming.

Second-Life Requirements

The following sections provide the requirements for a second-life battery energy storage system.

Energy Storage System

An ESS must be a packaged solution that utilizes second-life PEV battery packs configured to achieve the required design output that aligns to the application requirements. The packaged solution must be contained in an enclosure(s) that maintains environmental conditions, such as temperature, within the design limits and appropriate National Electrical Manufacturers Association (NEMA) ratings as well as the American National Standards Institute (ANSI) and

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[19] The future of automotive lithium-ion battery recycling: Charting a Sustainable Course; Linda Gaines 1 Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439, United States.

International Electrotechnical Commission (IEC). The ESS must include the required electrical, protective and monitoring equipment to safely charge and discharge each second-life vehicle battery as required to meet the ESS objectives. Safety interlocks must be included as required by federal, state and local codes.

The ESS output voltage range, frequency and phase requirements must be dictated by the host site requirement and operate in the utility-interactive mode in accordance with Institute of Electrical and Electronics Engineers (IEEE) 1547[20] – Standard for Interconnecting Distributed Resources with Electric Power Systems. The inverters must be certified by an Occupational Safety and Health Administration (OSHA) Nationally Recognized Testing Laboratory (NRTL) to comply with UL1741[21] tests for multimode inverters with the features described herein. The ESS must be fully automated for the specified application and compatible with the host site and meet CAISO interconnect requirements. The ESS must have a human machine interface (HMI) that clearly provides ESS status and alarms with the ability to view additional details of individual battery packs.

As required by the host site, the appropriate mechanical foundation and fencing, must be provided.

The ESS must be an integrated solution with switchgear, transformer, inverters, battery management system and batteries as required to provide system reliability and safety.

In addition to active power output control, the inverters must have the capability to adjust the power factor by adjusting the output reactive volt-amperes.

Electrical Interconnection on Grid

Many regulatory requirements must be met within the California ISO to maintain reliability and accessibility to the California power grid. California ISO provides open and non-discriminatory access to the bulk of the state's wholesale transmission grid, which is supported by a competitive energy market and comprehensive infrastructure planning efforts. For a resource to be considered as an ancillary service provider, specific criteria and operating characteristics must be met. The areas of primary focus within this document are specifically related to the regulation down or regulation up ancillary services category.

Resource bids can and will only be accepted after the scheduling coordinator is in possession of a current certificate issued by California ISO confirming the resource complies with California ISO's technical requirements for providing the ancillary service concerned. Scheduling coordinators can apply for ancillary services certificates in accordance with the requirements for considering and processing such applications Service Requirements Protocol (ASRP) of the California Independent System Operator Corporation Fifth Replacement Electronic Tariff[22] and

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[20] http://grouper.ieee.org/groups/scc21/1547/1547_index.html

[21] http://ulstandardsinfonet.ul.com/scopes/1741.html

[22] http://www.caiso.com/Documents/CombinedPDFDocument-FifthReplacementCAISOTariff.pdf

California ISO's operating procedures. If at any time California ISO's technical requirements are not being met, California ISO may withdraw the certificate for the resource concerned. These operating characteristics and technical requirements are outlined herein.

Operating Characteristics

Within the California ISO system, a particular set of operating characteristics must be met to qualify as a resource through California ISO.

1. The rated capacity of the resource must be 500 kilowatt (kW) or greater unless the resource is participating in an aggregation arrangement approved by California ISO. The rated capacity of 500 kW must be capable of providing at least 500 kW of regulation electrical power.
2. The maximum amount of regulation to be offered must be capable of being reached within a period of 10 minutes.
3. A resource must also be able to increase or decrease real power levels immediately in response to signals from California ISO's energy management system (EMS) control. The intent is for California ISO to maintain sufficient resources that are immediately responsive to the California ISO's EMS control to provide sufficient regulation service to allow California ISO Balancing Authority Area to meet North American Electric Reliability Corporation and Western Electricity Coordinating Council reliability standards and any requirements of the Nuclear Regulatory Commission (NRC) by continuously balancing resources to meet deviations between actual and scheduled demand and to maintain interchange schedules.
4. The capacity offered as regulation by a resource must be dispatchable on a continuous basis for at least 60 minutes in a day ahead market (DAM) and at least 30 minutes in the real time market (RTM).
5. Lastly, the resource should meet or exceed the minimum performance threshold for responding to California ISO's EMS control signal. The minimum performance threshold of 50 percent is applicable for a resource to offer regulation up and regulation down capacity. Additional details are further outlined within the referenced document.

Technical Requirements

In addition to the operational characteristics, detailed technical system requirements must be met such as control, monitoring and voice communications.

A control system must meet the minimum performance standards for communications and control outlined by California ISO and published on their website. The control system provided within a resource should be administered with a direct, digital, unfiltered control signal. The resource must be capable of receiving unfiltered control signals generated from the California ISO EMS through a standard California ISO direct communication and direct control system. The resource response (in megawatts [MW]) to a control signal must respond immediately, without manual operator intervention, to control signals and needs to sustain a specific ramp rate within specified regulation limits, for each minute of control response (MW/minute).

Ancillary service providers for non-generator resources, such as the case for subject second-life battery applications, may define a ramp rate for operating as generation and/or a ramp rate for operating as load.

Monitoring/Telemetry:

A resource providing regulation must have a standard California ISO direct communication and direct control system to send signals to the California ISO EMS for California ISO EMS to dynamically monitor, the following as a minimum requirement:

- Actual real power level (MW)
- Power high limit (MW), low limit (MW) and rate limit values (MW/min) as selected by the resource operator
- In-service status indication confirming availability of regulation service.

Ancillary service providers for non-generator resources (whether or not the resource uses regulation energy management) must provide California ISO the following additional telemetry data:

- Resource ramp rate when operating as generation (MW/min)
- Resource ramp rate when operating as load (MW/min)
- The maximum instantaneous ability to produce or consume energy in MW
- The maximum capability to provide energy as expressed in megawatt hours (MWh) over a fifteen (15)-minute interval.

For additional detail on requirements regarding a Certificate for Regulation refer to California ISO Corporation, Fifth Replacement Electronic Tariff July 1, 2013, Appendix K Ancillary Service Requirements Protocol (ASRP), PART A CERTIFICATION FOR REGULATION.

Vehicle Battery Pack Types

The ESS must be designed to integrate several vehicle battery packs into a working ESS. Battery packs are composed of modules that are contained in a single unit. Modules are composed of one or more cells where a single cell is the smallest energy storage component of the pack. Under the California Energy Commission Contract 600-12-016, CTC procured PEV batteries and their associated materials for use as test materials for this project. Three varieties of lithium-ion battery systems were procured as test materials for this effort, corresponding to three types of PEVs. These systems were manufactured by Electric Vehicles International (EVI), VIA Motors (VIA) and Electric Vehicle Add-On Systems (EVAOS).

Electrical Interconnection of Second-Life Vehicle Battery Packs

A combination of series and parallel strings were used to obtain the power and energy requirement of the ESS using available second-life vehicle battery packs (SL-VBPs). The configuration could range from a dedicated bi-directional inverter for each battery pack, to some combination of parallel battery packs connected to an inverter. Consideration must be given to battery pack voltage limits (both charged and discharged states), available energy, limits of operation and degradation, overall ESS efficiencies, available hardware components and cost effectiveness.

Each battery pack must have a dedicated BMS that must be used to protect the battery pack. It must consist of a combination of sensors, controller, communication and computation hardware with software algorithms designed to determine the maximum charge/discharge current and duration from the estimation of SOC and SOH of the battery pack. If not provided with the battery pack, it must be added to the battery pack.

Each BMS must include a communication port and protocol that provides key battery parameters about the battery pack to the overarching software control system.

The intent is not to redesign the battery packs, but to use existing connections for the following:

- BMS data communication
- Method for battery pack case grounding
- Connection method to the high-voltage DC bus
- Connection method for low voltage for any required control signal.

A method to individually perform cell balancing on each battery pack must be included. Cell balancing must be performed as required by a means which will not degrade the overall performance of the ESS. The ability to electrically isolate each battery pack must be included to enable cell balancing and to enable the ability to isolate faulted battery packs.

Mechanical Mounting for the Interconnected Battery Packs

The second-life battery ESS must be installed in a designated area within a building or within a container express (CONEX) type enclosure that could be mounted outdoors.

The design of the second-life battery ESS must take into account all aspects of the local environmental factors to ensure personnel and equipment safety. The second-life battery ESS must meet all applicable international, state, local building codes, fire codes and safety regulations per the California Building Standards Commission. Occupant safety must be maintained through the entire design, build and system operations. The mechanical structure for the SL-VBPs must be designed to prevent failure during local natural phenomenon such as seismic activity, hurricane, etc. The Seismic Design Code Principles for natural disaster prevention can be found in the California building code. The battery must be mounted in an orientation approved by the original equipment manufacturer (OEM) with the recommended clearances, mounting and interconnection taken into account. The batteries and balance of plant devices must be mounted in a manner where they are easily maintained and replaced.

Cooling Requirements for the Interconnected Battery Packs

The physical environment of the SL-VBP assembly must be an enclosed area with an environmental control system to properly condition the space. Limits on battery space conditions must be determined from battery and electrical equipment minimum and maximum design specifications, which must include both thermal and moisture recommendations. A thermal management system (TMS) must be included for battery packs and balance of plant components that require thermal management. The TMS must be designed to protect the battery pack from overheating. If required, liquid cooling ports must be included.

Battery cells are vulnerable to overheating due to charging/discharging and excessive ambient heat. Battery cooling must be addressed with the battery pack layout and design. Battery selection governs the final design's cooling method, with air and liquid cooling common methods currently use. The cooling system's overall size and capability must be determined by the design, demand profiles and the battery manufacturer's cooling specifications. Testing must be performed to determine the cooling requirements for the batteries if they are unavailable elsewhere. Automated methods must be in place to electronically isolate and de-energize individual batteries in the event of (or to prevent) a thermal runaway.

Some power electronics have susceptible temperatures limits. The physical location and outside environment of the second-life EES can determine how much heat the environment will contribute to the temperature of the electronics. The batteries, inverters, converters, controls and all other electronic devices used in a second-life battery ESS must be rated for maximum and minimum operational temperatures; the TMS must keep the system safely operating within the manufacturers' recommended temperatures.

The cooling requirements for inverters, converters, HMI and other electrical components must be addressed with the layout and mounting design to provide acceptable operational temperatures for the electronics. The final design's cooling method must be adequate to meet recommended power electronics operating temperatures during all power output scenarios. The cooling system's overall size and capability must be determined by the individual manufacturer's components, cooling specifications and the integrated design.

Software Control System

The control system must consist of a combination of hardware components, associated software and network components. The control system must be a supervisory control and data acquisition (SCADA) system. It must include at a minimum, the master controller, HMI, programmable logic controller (PLC), metering, data historian, battery management systems and remote access (monitoring/control). Power/energy monitoring connections to the grid must be performed utilizing revenue grade metering.

The control system must include the ability for both manual and automatic operation of all system components in various control modes. The control system must perform the following high-level functions:

1. Control the charging and discharging of the ESS in an efficient and safe manner while optimizing the operation and life of the storage components
2. Automatically perform individual cell balancing as required to maintain overall ESS outputs
3. Monitor and control interoperation of system metering and battery system to optimize the efficiency and cost to deliver real and reactive power to the critical loads

4. Provide an HMI for local viewing as well as remote monitoring of the system to trend, export and generate reporting data
5. Meet the control system key parameters and provide time relational charted data with recording rates of no greater than once per minute
6. Provide the user capability to monitor and collect system performance for the following parameters
    - Line voltage root mean square (RMS)
    - Phase voltage RMS
    - Line current
    - Voltage harmonics
    - System frequency
    - SOC
    - Operating status
    - Mode of operation
    - Site metering data; including real and reactive power flow and direction, voltage and frequency
7. Ensure the International Organization for Standardization communications are consistent with current standards such as:
    - Modbus transmission control protocol/Internet protocol (TCP/IP)
    - International Electrotechnical Commission (IEC) 61850
    - IEC 60870-5-101
    - IEC 60870-5-104
    - Distributed network protocol (DNP).

Safety Requirements

Personnel and property safety is a major concern for a second-life battery ESS. Proper safety features must be addressed during the design, installation and maintenance of a second-life battery ESS throughout the remaining life of the batteries. The second-life battery ESS design and installation must meet all applicable international, state and local building codes, fire codes and mandated safety regulations. The required construction permitting for building construction, fire protection and occupant safety must be obtained.

Depending on the physical location of the second-life battery ESS installation, the following factors must be considered.

- Seismic protection must be considered during the design to mitigate failure during an earthquake.
- Liquid-tight secondary containment must be used per Environmental Protection Agency (EPA) regulations.
- The SL-VBP enclosure must have proper lighting to adequately illuminate potential safety hazards as well as properly light the work area.

- Proper signage must be installed and must be visible alerting personnel of potential hazards such as high voltage, caustic materials, acids, etc.

- Satisfactory ventilation must be provided. The amount of ventilation is dependent on battery chemistry and layout.

- A smoke detection system must be installed to alert required personnel of an emergency.

- Fire suppressant devices must be accessible and or automated and capable of providing adequate fire suppression for the battery chemistry and surrounding environment.

Codes and Standards

Additional specific codes and standards for implementation of the second-life battery stationary ESS in California not previously identified include (but are not limited to):

- NEC[23] (National Electric Code)
- CBC[24] (California Building Code)
- CFC[25] (California Fire Code)
- UL1973[26] (Safety standard for stationary batteries used in energy storage applications).

Preliminary Design Concept for Second-Life Battery Application

This preliminary design for second-life battery applications is based on the technical requirements to package the PEV second-life batteries for use as a stationary energy resource.

This section discusses the preliminary design concept and assumptions that were used to develop the concept. A majority of the effort was in determining how the batteries could be configured and grouped to achieve the energy storage system (ESS) objective to support small utility applications as well as continuing the possibilities with a commercial application behind the meter. Adequate energy as compared to the power output to support ancillary services applications was another objective which California ISO requires 500 kW minimum with a 30-minute charge and discharge time to certify the system. Upon the selection of a host site, additional details will be used to further develop this concept. This will include site specific requirements to further define the most lucrative application. A combination of series and parallel strings is typically used in battery packs to obtain the power and energy requirement for the vehicle. These SL-VBPs can be configured to meet the needs of an ESS.

A host of energy storage technologies are in various levels of development, all trying to achieve DOE’s price point objectives and technical performance criteria. Many organizations are looking

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[23] http://www.nfpa.org/codes-and-standards/document-information-pages?mode=code&code=70

[24] http://www.bsc.ca.gov/Home/Current2013Codes.aspx

[25] http://www.bsc.ca.gov/Home/Current2013Codes.aspx

[26] http://ulstandardsinfonet.ul.com/outscope/outscope.asp?fn=1973.html

at their technologies with the goal of reducing the life cycle cost. It is a modular and scalable approach that could leverage many battery chemistries in an effective manner. This concept provides a flexible design that accommodates a variety of SL-VBPs and is not dependent on the chemistry. Considerations were given to battery pack voltage limits charged and discharged states), available energy, limits of operation and degradation, overall ESS efficiencies, available hardware components and cost effectiveness.

Assumptions

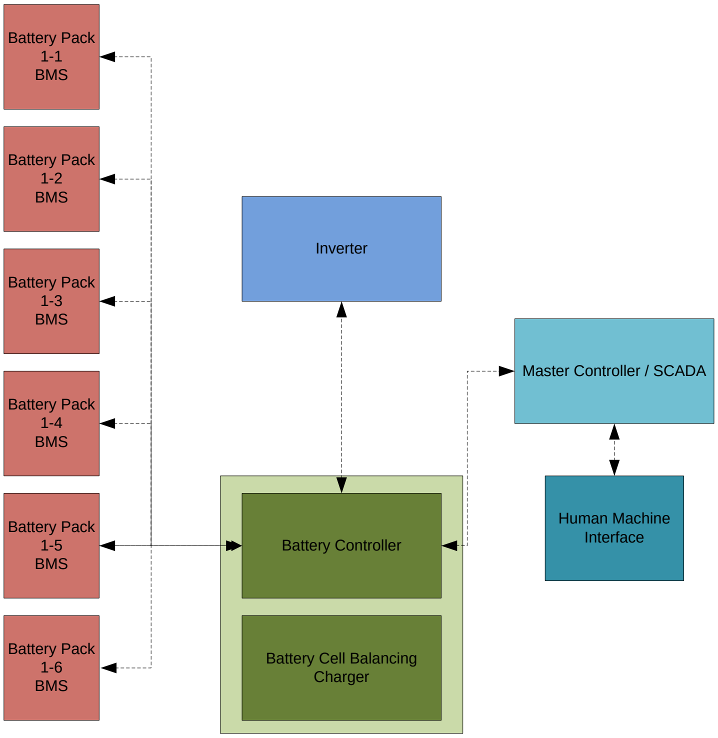
The preliminary design concept is based on several assumptions.

1. The grid-level energy storage system is sized at 1 MW, 500 kWh and configured with four each 250-kW subsets.
2. Each 250-kW subset consists of two each 125-kW battery modules.
3. Battery parameters are based on battery packs currently being tested under Agreement Number: 600-12-016, Vehicle-to-Grid (V2G) Testing and Demonstration with Department of Defense (DoD). These battery packs consist of 348 prismatic lithium cells with three parallel series each containing strings of 116 cells.
4. Batteries and components require cooling. The batteries are water cooled, while the power electronics require a conditioned area in the container or be placed outside the container. (The intent is to reduce the parasitic losses as much as possible and thus operate with minimal cooling.)
5. Each battery pack has usable energy storage at or below 80 percent rated capacity.
6. Second-life battery pack energy is assumed to be 13.8 kWh.
7. The maximum C-Rate is less than a 2C rate (1.8C is recommended).
8. The ESS is assembled in the International Organization for Standardization (ISO) containers.

Preliminary Design – Drawing Package

Figure 49 shows the communications within one of the 125-kW battery modules, which consists of six battery packs, each with a dedicated BMS. These battery modules are configured in parallel and will feed a single inverter. Each 125-kW battery module will have a dedicated battery controller that will coordinate the interactions of the battery packs through communications with the dedicated BMS and coordinate interactions with the inverter. The battery controller will control a charger that will be used to provide cell balancing of each battery pack in the module. The battery controller will communicate with a master controller. The master controller will provide the interaction to the grid and each of the eight battery controllers for this 1-MW ESS concept. The master controller will have a human machine interface that will provide the user with status of the ESS, battery pack status, system output parameters, alarm indications and operating modes. CAISO communication will also be accomplished through the master controller.

Figure 49: 125-kW Battery Module Communications



Source: Concurrent Technologies Corporation

Determination of Condition Diagnostic Protocol

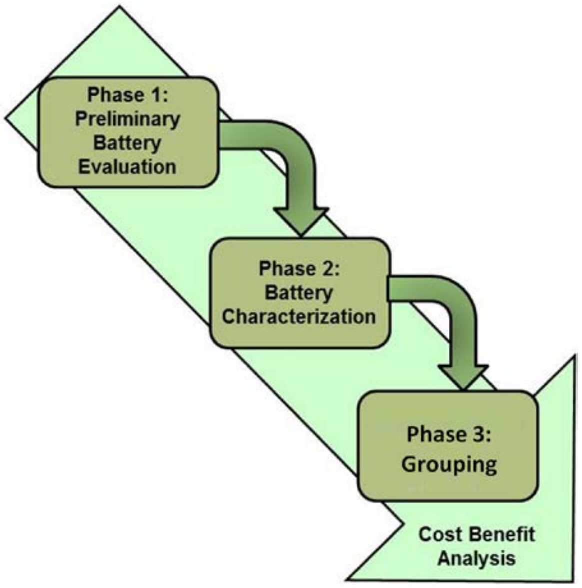
EV batteries are typically replaced when they reach 70–80 percent of their rated capacity. Although the batteries are not optimal for vehicle applications, they still have the potential to be repurposed in other applications. When new, the energy storage capacity of a typical EV battery pack is 22–32 kWh. To use these batteries in the ancillary services market, one would need more than 39 packs for a 1MW-size second-life energy storage system when accounting for a 20 percent loss of rated capacity due to customary battery degradation. Allowing for development and integration flexibility of these systems, a universal determination of condition (DoC) diagnostic protocol is needed to optimally integrate dissimilar battery systems. Understanding the value of used vehicle batteries will help drive aftermarket applications. This effort to develop a universal DoC diagnostic protocol will support the value of potential aftermarket applications of vehicle batteries.

The objective of this task was to develop a universal DoC diagnostic protocol and recommend standard test methods for predicting optimal second-life applications of used EV batteries. This included investigating different test methods and battery attributes and defining the potential performance benefits of testing prior to integration into a large-scale energy storage system. Testing and evaluating included quantifying the benefit of testing at the cell level, module level or pack level to configure a large second-life energy storage system. Battery performance was only one aspect to consider when implementing repurposed batteries. Safety, regulatory requirements and liability concerns were also addressed.

Protocol Development

CTC developed and presented a draft DoC diagnostic protocol on November 22, 2016; a final update was provided to the California Energy Commission during the Critical Project Review on December 13, 2016. As illustrated in Figure 50, the protocol was based on three phases identified as 1) Preliminary Battery Evaluation, 2) Battery Characterization and 3) Grouping. The arrow passing through the phases is focused on a safe and cost effective approach to evaluate batteries having potential for a cost benefit. This protocol does not address the recycling at the end of its second-life use in the large-scale storage farm application. Recycling continues to be an important area in need of attention following first vehicle use or second-life use in stationary applications.

Figure 50: DoC Diagnostic Protocol



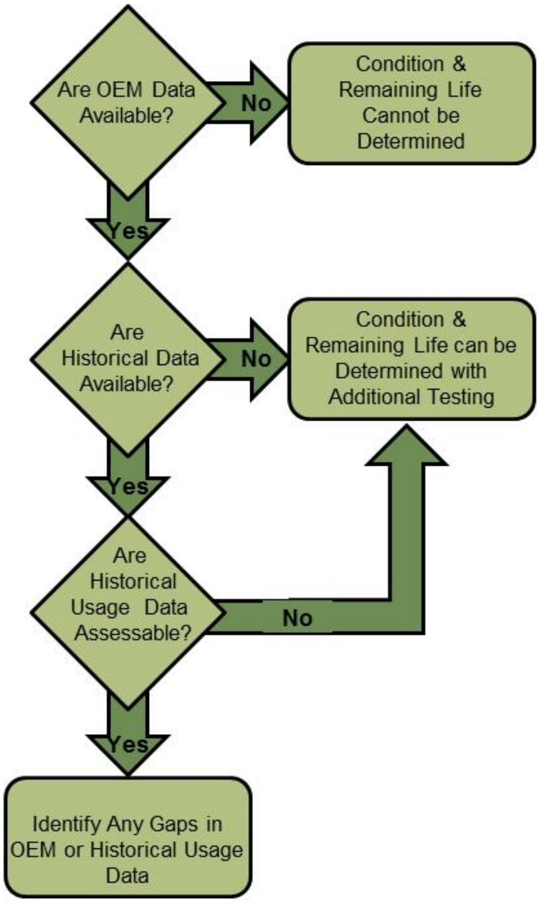
Source: Concurrent Technologies Corporation

Preliminary Battery Evaluation

The Preliminary Battery Evaluation phase, shown in Figure 51, is designed to obtain an understanding of how and where each battery pack was used in its initial application. This phase includes obtaining battery specifications from the OEM; these specifications are critical to evaluating the battery’s condition/health at the time of receipt for second-life applications. This includes a visual inspection for cracks, swelling or obvious damage to the component being evaluated. OEM data provides a baseline for comparison to the second-life battery’s initially measured performance. By evaluating the battery’s current performance against its performance when new, a current SOH can be evaluated and its remaining useful life can be estimated.

Battery manufacturer specifications are used to identify parameters such as rated capacity, voltage and temperature limits, internal resistance and pack configurations. Additionally, historical data from a BMS would be documented and could include parameters such as total usage, SOC, mean DOD, SOH, specific cell information and environment conditions. The key is to leverage as much of the historical data as possible to provide insight on the battery's fitness for second-life use. Historical information such as the geographical location, storage/maintenance conditions, application of the battery and data tracking performance during its first application, can provide insight into its condition and support conclusions drawn from physical testing. Based on this evaluation, the next phase could be focused on a specific issue of concern for the battery pack or require additional testing of the battery pack, modules or cells.

Figure 51: Preliminary Battery Screening



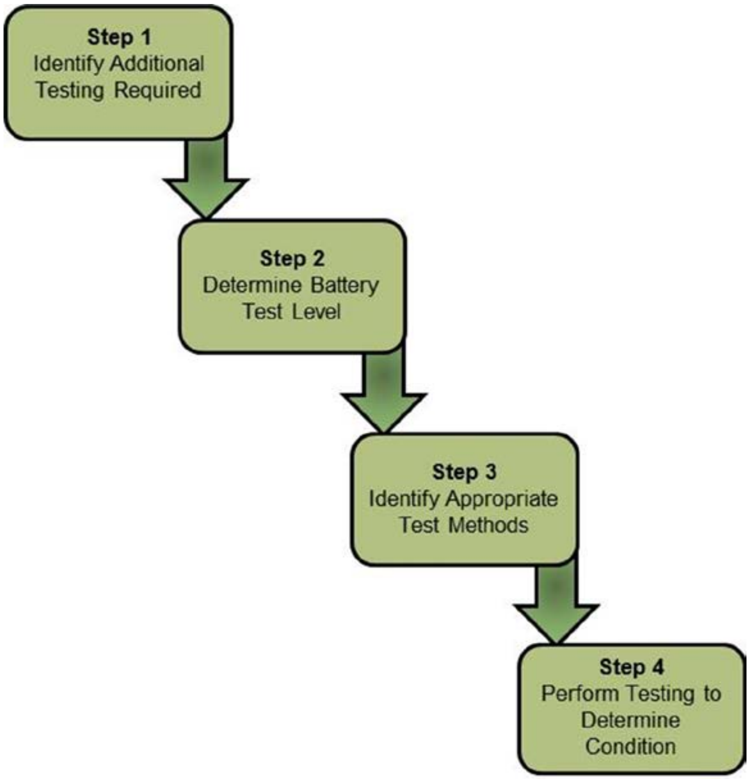
Source: Concurrent Technologies Corporation

Battery Characterization

The Battery Characterization phase, shown in Figure 52, focuses on testing each battery. Testing can be accomplished at the pack, module or cell level. Disassembly and testing the battery pack at the module and cell level provides more comprehensive data on the health of a given battery pack than does pack testing, but also requires additional effort. A good rule of thumb is to test at the lowest practical component level.

When cells and modules are connected, the assembly is only as good as the weakest individual component. Therefore, to avoid wasted capacity, one should strive to group batteries of similar characteristics.

Figure 52: Battery, Module or Cell Characterization



Source: Concurrent Technologies Corporation

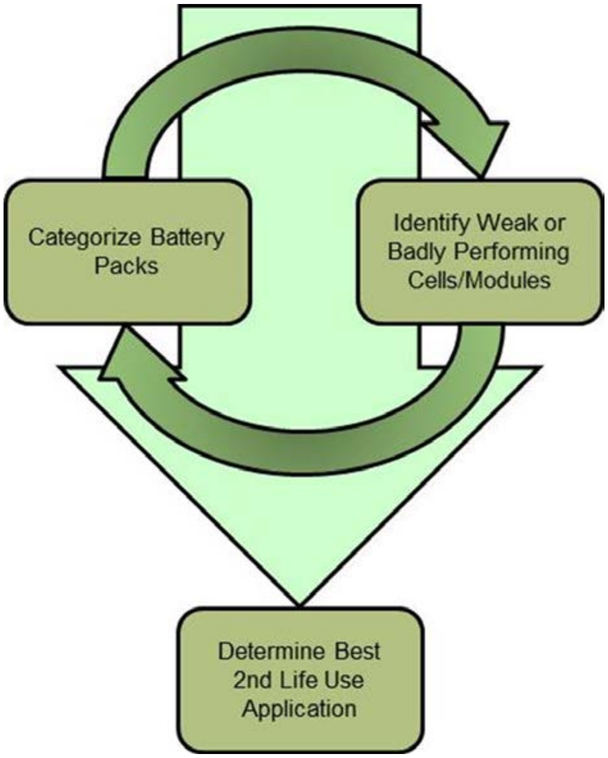
Whether testing at the pack, module or cell level, the data are focused on understanding battery health with the ultimate goal of combining closely matched batteries (modules or cells) to be put into a second application. The primary characteristics of battery condition are remaining capacity, efficiency and internal resistance; cell voltages and operating temperatures are of secondary importance. These characteristics are generally interdependent, for example, an increase in internal resistance causes a reduction in battery efficiency and the ability to deliver power. If available, a BMS could be used to obtain additional data, such as maximum cell/module temperature and cell voltage. These data can provide insights into discrepancies between cells and the general stability of the battery by comparing cell voltages. Cell voltages of a similar magnitude among all battery cells indicate a well-balanced battery, while large discrepancies indicate poor balancing or specifically one or more deficient cells within the battery. Batteries having minimal differences among all of its cells will provide longer-lasting, safer and more reliable performance.

Grouping

The last phase of the DoC protocol is the ranking or grouping of batteries, modules or cells as shown in Figure 53. The intent is to group batteries, modules or cells that have a similar use history and present state of health. The methodology defines four unique categories with the first three containing usable batteries while the last category is for batteries needing to be directly recycled / reclaimed as opposed to being used for second-life applications.

The four recommended categories focus on key performance/characterization parameters including energy storage capacity, battery modules and cell temperatures, internal resistance and key voltages (when comparing modules and packs). Each category contains batteries, modules or cells meeting a minimum threshold. Additional subdivision could then be made to group batteries, modules or cells of similar performance levels before introducing them into their second-life application. At this point, battery packs could be assembled for specific applications to achieve the maximum benefit.

Figure 53: Battery, Module and Cell Sorting



Source: Concurrent Technologies Corporation

An example where grouping is necessary is the construction of supplementary power storage and regulation banks. Currently, there are several research and demonstration projects investigating the use of second-life batteries in different configurations and applications that include microgrids, peak demand, renewable ramping, frequency response and others. A majority of these projects operate at a total capacity of 100 kWh, which would require five or more sets of second-life EV batteries. For grid-level storage, units having megawatts/megawatt-hours of output/storage are required; such applications require a minimum of 55 vehicle-sized battery packs to provide the required grid-level power and energy storage.

Underwriters Laboratories Recent Activity

The Underwriters Laboratories Incorporated (UL) recently initiated the development of ANSI/CAN/UL 1974, The Standard for Evaluation for Repurposing Batteries. As the name implies, this standard covers the sorting and grading process of battery packs, modules and cells originally configured and used for other purposes and intended for repurpose use applications.[27] The draft standard is in preliminary review as of the date of this report. There are similarities between the standard and what is presented in this DoC protocol report, with the UL standard including factors beyond those discussed above. The UL standard adds greater specificity to the process of sorting, inspecting and grading battery packs, modules and cells.

UL relies on the battery OEM to establish grading criteria for assessing cells and modules. It also suggests a six-sigma rating system to establish grades based on ranges of sigma values with the baseline or standard being the OEM battery parameter. UL recommends additional testing to support battery health determination. The testing performed by CTC in this task provides additional detail on the development and justification for evaluation of the parameters suggested by the draft UL report. Neither exhaustive documentation nor complex examination instructions were required in the CTC approach to battery assessment. While the UL report refers the battery evaluation back to the OEM, the CTC methodology approached evaluation from a third-party perspective and provided basic recommendations, as well as two methods for grading batteries based on the OEM’s battery specification.

After reviewing the draft standard and developing the DoC protocol, it is clear that an industry grading standard must be set by a governing body to accelerate and standardize the use of recycled EV battery packs. Once finalized, UL 1974 is expected to be the standard for all manufacturers to follow when repurposing batteries which incorporates the testing performed by CTC.

DoC Laboratory Testing

The DoC laboratory testing leveraged testing assets used in the UCSD laboratory testing effort (detailed in CHAPTER 3: Laboratory Research, Testing and Analysis). In this case, a thorough history existed for each battery. A total of 28 Valence U27-12XP batteries modules were evaluated; they were previously exercised as two battery packs each having 14 modules in series. Based on the laboratory testing, the condition of these battery packs was well known. The energy storage capacity was known, and there were no faulted modules. The V2G Pack was exercised with a vehicle drive profile followed by a V2G profile, and the Control Pack was exercised with only the vehicle drive profile.

Test Equipment, Software and Interconnections

The following test equipment and materials were used to perform module testing:

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[27] http://www.shopulstandards.com/productdetail.aspx?ProductID=UL1974_1_B_20170602

- NH Research 9200 battery charge/discharge test system
- Valence U-BMS-XP-LV Model 1 SLP U27 battery management system
- MEASURpoint DT8874 data acquisition unit
- Omega type K thermocouples.

The battery module and associated BMS was configured and wired to the NH Research 9200 battery charge/discharge test system (9200). The 9200 has three independent test channels that allow for independent testing of three modules at a time. NH Research's Enerchron test management software provided the capability for complex, dynamic test sequences and was used to collect and archive data measurements. Additional data acquisition (DAQ) was performed with an integrated device (MEASURpoint DT8874) that integrates with the Enerchron test management software. Each DAQ device channel consists of its own high-resolution 24-bit architecture, individual channel measurement range and full isolation from all other channels. Additionally, temperature measurement channels are independently programmable for any thermocouple type (B, E, J, K, N, R, S and/or T) allowing flexibility in the selection and use of thermocouples.

The test setup included four thermocouples mounted on the module case along with a thermocouple for monitoring ambient air temperature. Additionally, outputs from the BMS were monitored for voltage limits and charge completed status.

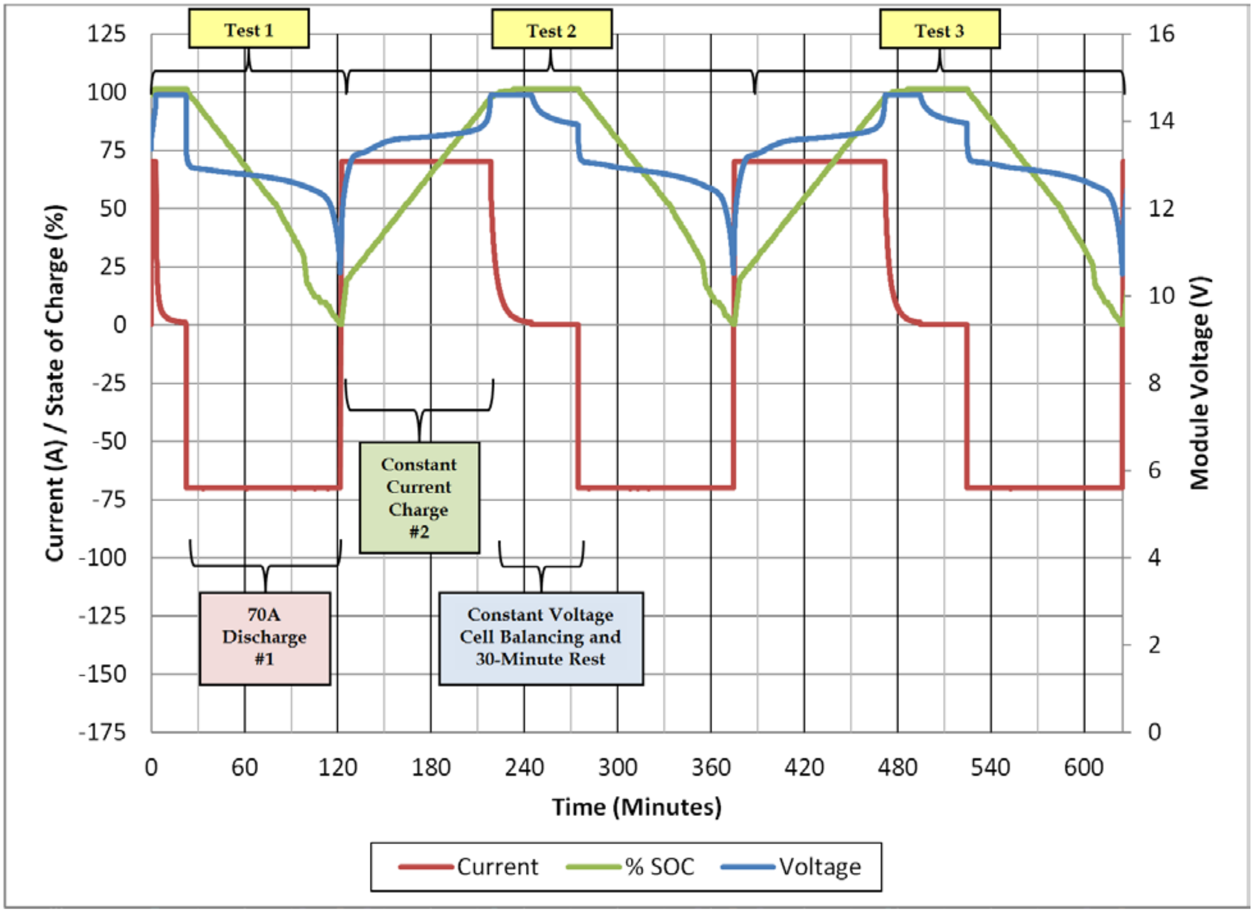
Execution of Test Protocol

Data of interest were captured by monitoring the battery modules during execution of two tests: 1) constant-current discharge to a low-voltage cut off (per the manufacturer's specification) and 2) high-current discharge pulses at several states of charge. Three identical test cycles were performed; however, due to time constraints, sufficient time was not allotted to allow the battery temperature to return to ambient temperature before repeating the tests. The outputs for each group of three tests were averaged to determine the representative value for the battery.

Figure 54 illustrates the three constant-current-discharge cycle tests conducted to evaluate the battery capacity. The test control program began by fully charging a battery and balancing cells in accordance with the manufactures' procedures. The charge started at a constant current charge of 70 amps until the battery voltage reached 14.6 volts, at which point the charge transitioned to a constant-voltage profile until either the BMS signaled charge complete or the constant voltage segment duration of 1.0 hour was exceeded. This was followed by a 30-minute rest period.

The battery was discharged at 70 amps until the battery module voltage reached 10.5 volts or one of the cells was less than 2.3 volts, as monitored by the BMS. Discharge concluded with a 30-second wait period. At this point, charging initiated at the same charge profile defined previously. After the charge completed, a rest period of 30 minutes was performed. This sequence of charge, rest, discharge and rest was repeated two more times for a total of three constant-current capacity tests over approximately a 12-hour period.

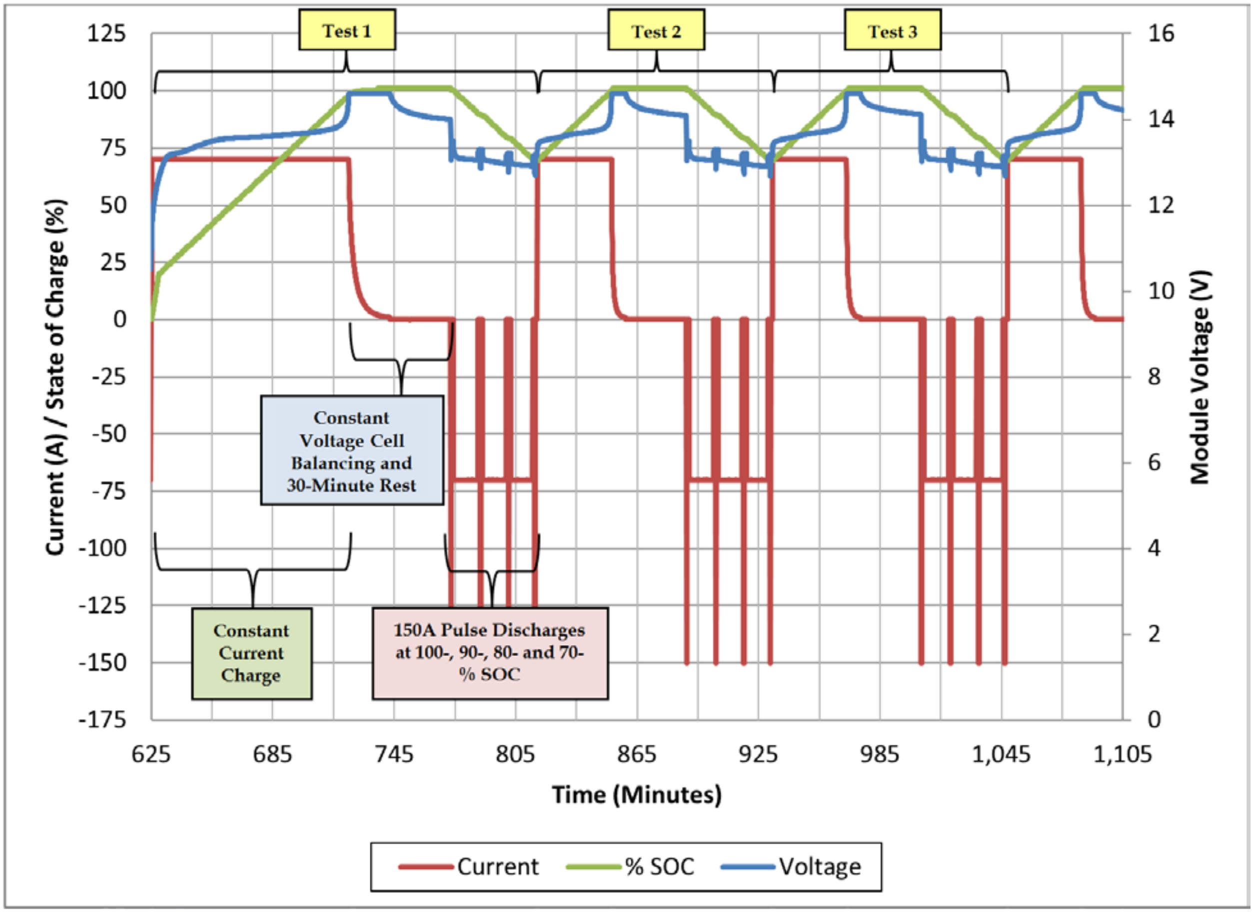
Figure 54: Constant-Current-Discharge Segment



Source: Concurrent Technologies Corporation

Figure 55 illustrates three high-current pulse tests that followed the capacity tests. Each test contained four 20-second durations, 150-amp pulses at states-of-charge of 100, 90, 80 and 70 percent. The voltage drop across this period of time was used to calculate the battery's internal resistance at multiple states of charge. Starting with the battery module fully charged, the battery module experienced the first 20-second, 150-amp pulse at 100 percent SOC followed by a one-minute rest. A constant current discharge of 70 amps was then executed until the battery module SOC dropped to 90 percent. A rest period of one minute was executed, followed by a 20-second, 150-amp pulse. This sequence continued for the 80 and 70 percent SOCs. The battery was then fully charged based on the same charge profile as described previously and the high-current test was repeated two more times. This sequence of testing was completed within an 8-hour period.

Figure 55: Pulse-Discharge Segment



Source: Concurrent Technologies Corporation

Results of Battery Module Testing

Capacity, efficiency and internal resistance are important battery characteristics to examine when attempting to determine the condition of batteries for a second application. Capacity is the battery's fully-charged available energy in ampere-hours (Ah) and is proportional to the maximum amount of energy that can be extracted from the battery. Efficiency is the ratio of the energy discharged from the battery to the energy required to charge the battery. Internal resistance, most simply, is the difference between a battery's resting (i.e., open circuit) voltage and voltage under load. Internal resistance is caused by parasitic reactions in the electrolyte and on the electrodes and limits the power the battery can produce. Temperature was measured at four battery locations; these measurements were made to potentially determine a location of battery breakdown and provide other insights to aid in determining battery condition. Battery module voltage, current, power, energy, capacity and temperatures were collected at 2.0 hertz during testing.

A summary of the capacity, remaining life and efficiency for the V2G Pack (drive + V2G profiles) and Control Pack (drive profile only) after completing laboratory testing can be found in Table 29. It provides the mean of three capacity measurements and the associated standard deviation as the temperature/capacity increased. The mean standard deviation of batteries from the Control Pack were overall higher (0.38 Ah versus 0.29 Ah) than the V2G Pack and so was the mean capacity of batteries from the Control Pack (116.4 Ah versus 106.6 Ah). This difference in battery capacity increase between each test and the overall higher mean battery capacity for the Control Pack was attributed to temperature having a greater positive affect on the Control Pack versus the V2G Pack.

Table 29: Basic Comparison of Tested Packs

V2G Pack					Control Pack				
Battery	**Mean Capacity (Ah)**	**Std. Dev. (Ah)**	**Tested Capacity (%)**	**Mean Efficiency (%)**	**Battery**	**Mean Capacity (Ah)**	**Std. Dev. (Ah)**	**Tested Capacity (%)**	**Mean Efficiency (%)**
A7	112.8	0.26	81.7	93.1	B8	118.6	0.38	85.9	93.5
A8	112.3	0.20	81.4	93.0	B7	118.3	0.39	85.7	93.5
A14	111.7	0.35	80.9	93.0	B12	117.4	0.34	85.1	93.4
A1	110.9	0.28	80.4	92.7	B10	117.0	0.45	84.8	93.2
A9	110.3	0.15	79.9	92.8	B14	117.0	0.45	84.8	93.3
A10	109.5	0.41	79.4	92.0	B9	116.5	0.31	84.4	93.4
A11	106.1	0.25	76.9	92.8	B11	116.4	0.38	84.3	93.4
A13	106.0	0.40	76.8	92.4	B2	116.3	0.40	84.3	93.3
A6	105.6	0.27	76.5	92.4	B1	116.1	0.36	84.2	93.3
A12	104.1	0.42	75.4	91.6	B6	116.1	0.34	84.1	93.4
A2	102.3	0.22	74.1	92.5	B5	115.9	0.41	84.0	93.4
A3	101.3	0.25	73.4	92.5	B4	115.2	0.37	83.5	93.2
A4	100.5	0.33	72.8	92.1	B3	115.0	0.33	83.4	93.3
A5	99.0	0.28	71.8	92.1	B13	114.1	0.40	82.7	93.2
Summary of Modules From V2G Pack					**Summary of Modules From Control Pack**				
Mean	106.6	0.29	77.2	92.5	**Mean**	116.4	0.38	84.4	93.3
Span	13.7	0.27	10.0	1.5	**Span**	4.5	0.14	3.3	0.3
Std. Dev.	4.5	--	3.3	0.42	**Std. Dev.**	1.2	--	0.9	0.10

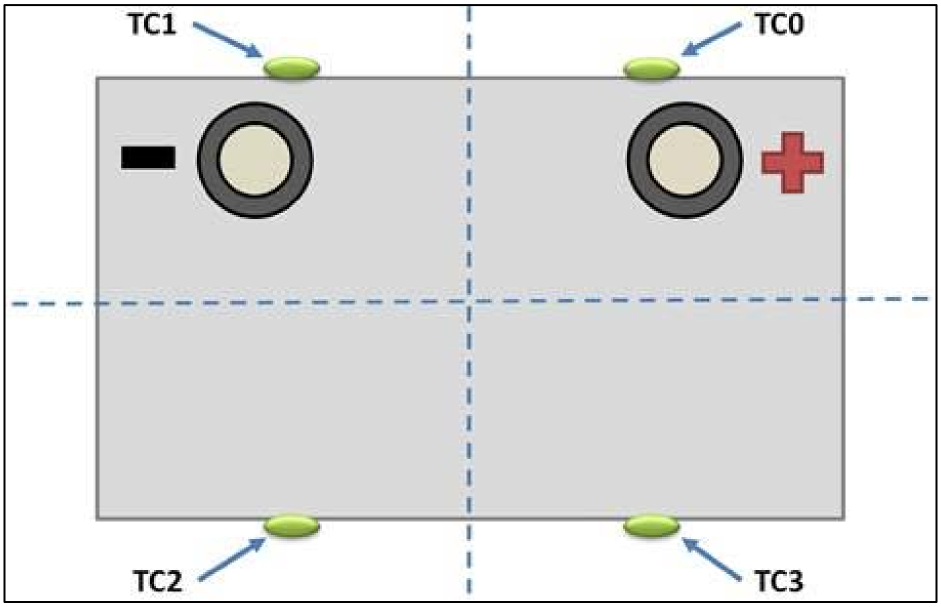
Source: Concurrent Technologies Corporation

Table 29 summarizes two basic indicators of battery condition—capacity and efficiency. The mean battery capacity from the V2G Pack is 106.6 Ah, which was 8.4 percent (~10 Ah) less than the Control Pack; the manufacturer's specified capacity for these batteries was 138 Ah. Values for the Control Pack were more consistent than those for the V2G Pack. The standard deviation for the V2G Pack capacity was 4.5 Ah, while the Control Pack had a much lower standard deviation of 1.2 Ah. The energy throughput on the V2G Pack was greater, resulting in more overall battery degradation, which was likely also causing greater variability in battery performance than that of the Control Pack. Knowing the V2G Pack experienced both driving and V2G test cycles while the Control Pack only underwent driving cycles supports the use of historical knowledge (application specifically) as verification of a battery's condition as determined by testing.

The mean efficiencies of both battery packs were comparable (less than one percent difference). Therefore, efficiency for the batteries used during laboratory testing did not appear to be a significant indicator of battery condition for these batteries.

Temperatures were recorded throughout the charge and discharge tests with four surface-mount thermocouples (TC0 through TC3) placed symmetrically on the battery sides (mid-height) at the locations shown in green in Figure 56; a fifth thermocouple probe was used to measure ambient temperature in the climate-controlled test bay. Temperature was recorded continuously by the DAQ. To simplify data for comparison, the minimum, maximum and mean temperature values for each thermocouple during each cycle were calculated and normalized by subtracting the mean ambient temperature during the same period.

Figure 56: Thermocouple Mounting Locations



Source: Concurrent Technologies Corporation

Table 30 and Table 31 show the mean battery temperatures (adjusted for ambient temperature changes) recorded by thermocouples TC0 through TC3. V2G Pack battery module temperatures were overall slightly higher than the Control Pack; this was expected based on the reduced battery capacity and higher internal resistance values found in the V2G Pack. However, when sorting the batteries by internal resistance, there appeared to be no significant relationship between temperature and internal resistance based on external battery temperatures.

Furthermore, capacity did not appear to correlate with battery temperature. Color formatting was used for temperature values in these tables to highlight trends and abnormalities in the temperature measurements. Red cells indicate higher temperatures, and blue cells indicate lower temperatures.

Table 30: V2G Pack Thermocouple Temperatures and Related Information

Module	Temperature* from Given Thermocouple (°C)				Mean Battery Temp.* (°C)	Capacity (Ah)	Internal Resistance (mΩ)
	TC0	TC1	TC2	TC3			
A12	11.5	4.0	9.4	10.0	8.7	104.1	5.08
A10	8.8	3.6	8.3	7.3	7.0	109.5	4.78
A5	6.8	6.5	9.6	9.3	8.1	99.0	4.28
A3	6.6	6.3	9.3	9.2	7.8	101.3	4.23
A4	5.2	4.6	9.6	8.8	7.1	100.5	4.23
A11	5.4	4.8	9.9	9.2	7.3	106.1	4.18
A6	5.0	4.9	8.3	8.1	6.6	105.6	4.18
A2	6.3	5.9	10.4	10.2	8.2	102.3	4.17
A13	4.8	4.4	10.8	9.6	7.4	106.0	4.13
A9	7.2	6.8	9.8	10.6	8.6	110.3	4.11
A1	6.2	4.5	10.2	9.8	7.7	110.9	4.05
A8	7.3	6.6	11.6	10.1	8.9	112.3	4.03
A7	5.6	5.5	10.6	9.7	7.8	112.8	3.94
A14	6.6	5.9	9.1	7.8	7.4	111.7	3.81
Mean	6.7	5.3	9.8	9.3	7.8	106.6	4.23

* Stated temperature represents the amount above ambient temperature.

Table 31: Control Pack Thermocouple Temperatures and Related Information

Module	Temperature* from Given Thermocouple (°C)				Mean Battery Temp.* (°C)	Capacity (Ah)	Internal Resistance (mΩ)
	TC0	TC1	TC2	TC3			
B13	7.0	5.6	8.6	9.6	7.7	114.1	3.90
B10	8.5	5.2	8.2	8.4	7.6	117.0	3.87
B4	5.5	4.5	7.5	8.0	6.4	115.2	3.81
B12	6.7	6.4	10.0	7.8	7.7	117.4	3.81
B11	4.6	3.9	9.4	8.6	6.6	116.4	3.77
B6	6.9	6.6	9.3	9.7	8.1	116.1	3.75
B5	5.3	3.8	9.2	8.9	6.8	115.9	3.75
B3	6.3	5.2	8.6	7.6	6.9	115.0	3.74
B2	4.8	3.7	9.5	8.0	6.5	116.3	3.74
B9	6.4	5.9	8.6	7.9	7.2	116.5	3.73
B1	6.9	4.8	7.1	7.5	6.6	116.1	3.70
B8	4.6	4.0	9.3	7.6	6.4	118.6	3.66
B14	5.5	3.8	8.3	8.0	6.4	117.0	3.58
B7	7.3	5.5	7.9	8.1	7.2	118.3	3.53
Mean	6.2	4.9	8.7	8.3	7.0	116.4	3.74

*Stated temperature represents the amount above ambient temperature.

The most notable observation from the surface-mounted thermocouple data (see Table 30 and Table 31) was that in most cases, the back side (thermocouples TC2 and TC3) of the battery had higher temperatures than the front side of the battery (thermocouples TC0 and TC1). The battery module was designed such that the Printed Circuit Board Assembly (PCBA) was mounted between the terminals so the entire block of cells was positioned about an inch or so back from the front and directly against the back of the battery case; therefore, the backside of the batteries is closer to the source of heat, which would keep this side of the batteries hotter than the front side. Therefore, the difference in measured temperatures is reasonable. Considering the limited insight provided by the thermocouple measurements and the time required to mount, collect and process the data, use of thermocouples is not recommended as a primary method to determine battery condition, assuming there is over-temperature protection from a BMS.

One notable observation can be found in Table 30 with battery modules A10 and A12 (the batteries in the V2G Pack with the highest mean internal resistance). Thermocouples TC1 and TC2 on each of these two batteries, measured lower temperatures on average than other batteries from the V2G Pack at these locations. However, for battery A12 (highest resistance), the thermocouple TC0 temperature was abnormally higher than all other V2G Pack batteries. This suggests that the battery A12 cell closest to the TC0 measurement area was failing badly and could have been the major contributor to the battery's high internal resistance.

Internal resistance is a key parameter in determining the performance of a battery. As a battery degrades, its internal resistance increases reducing the battery's ability to deliver power on demand. Battery failure can occur when the internal resistance increases to the point where the battery cannot supply a useful amount of power to an external load. The internal resistance of a battery can be calculated from data captured during a current step test.

A pulse current discharge was incorporated into the test profile to provide a means to calculate the internal resistance of each battery. During this portion of the test profile, the battery was subjected to a discharge pulse of 150 amps for 20 seconds. The pulse was executed in the test profile at 100, 90, 80 and 70 percent state of charge with a one-minute rest between each discharge pulse. This set of four pulses was then repeated three times. For the high-current-discharge portion of testing, the capture rate of the DAQ system was increased to 10 hertz to achieve the required data resolution for analysis and calculations.

Internal resistance was determined using a current step method, specifically the Verband der Automobilindustrie, Frankfurt am Main, Germany (VDA) method. With this method, the battery voltage and current are recorded as a pulse discharge is executed. The voltage readings of importance are before the pulse (U_1), immediately following the start of the pulse (U_2), the middle of the pulse (U_3) and the end of the pulse (U_4). The change in voltage divided by the current yield the internal resistance at each point during the discharge pulse (Ri). The equations are as follows.

$$Ri_{discharge,2s} = \frac{U_1 - U_2}{I_{discharge}}$$

$$Ri_{discharge,11s} = \frac{U_1 - U_3}{I_{discharge}}$$

$$Ri_{discharge,20s} = \frac{U_1 - U_4}{I_{discharge}}$$

The step method used was based on the aforementioned VDA approach with the only changes being the discharge pulse duration, causing U_3 and U_4 to be shifted one second and two seconds to the right (forward in time), respectively, to coincide with the midpoint and end of the discharge pulse profile, and the current discharge rate to match battery specifications. A summary of the internal resistance for the battery packs is available in Table 32 and Table 33 for the V2G and Control Packs, respectively. These tables show the mean resistance of all the battery modules in each pack at each SOC, the mean battery resistance through all ranges of testing, as well as the standard deviation of the mean battery resistance for each battery. The mean resistance for the V2G Pack was 12 percent higher than the Control Pack. However, the standard deviations show that the mean resistance in the V2G Pack was three times that found in the Control Pack. In all modules from both packs, the internal resistance at 100 percent SOC was much higher than anticipated, approximately double the resistance recorded at 90, 80 and 70 percent SOC. An explanation for this trend was not identified.

Table 32: Resistance of V2G Pack

	Resistance at State of Charge (mΩ)				Battery Mean (mΩ)
Battery	**100%**	**90%**	**80%**	**70%**	
A12	8.29	4.00	3.98	4.03	5.08
A10	7.91	3.70	3.71	3.78	4.78
A5	6.70	3.38	3.45	3.58	4.28
A3	6.85	3.33	3.35	3.42	4.23
A4	6.66	3.37	3.41	3.48	4.23
A11	6.83	3.26	3.27	3.35	4.18
A6	6.77	3.28	3.30	3.36	4.18
A2	6.79	3.21	3.31	3.38	4.17
A13	6.61	3.22	3.29	3.39	4.13
A9	6.71	3.21	3.22	3.29	4.11
A1	6.62	3.18	3.18	3.20	4.05
A8	6.54	3.15	3.17	3.28	4.03
A7	6.49	3.05	3.09	3.14	3.94
A14	6.20	3.00	2.99	3.05	3.81
Mean	**6.85**	**3.31**	**3.34**	**3.41**	**4.23**
Std. Dev.	**0.537**	**0.250**	**0.244**	**0.246**	**0.314**

Source: Concurrent Technologies Corporation

Table 33: Resistance of Control Pack

	Resistance at State of Charge (mΩ)				Battery Mean (mΩ)
Battery	**100%**	**90%**	**80%**	**70%**	
B13	6.41	3.04	3.07	3.08	3.90
B10	6.45	2.99	2.99	3.06	3.87
B4	6.27	2.97	2.95	3.05	3.81
B12	6.34	2.94	2.94	3.01	3.81
B11	6.24	2.93	2.94	2.96	3.77
B6	6.26	2.90	2.89	2.97	3.75
B5	6.18	2.93	2.93	2.96	3.75
B3	6.17	2.92	2.93	2.95	3.74
B2	6.15	2.91	2.90	2.98	3.74
B9	6.18	2.89	2.89	2.97	3.73
B1	6.06	2.89	2.88	2.97	3.70
B8	6.06	2.83	2.83	2.91	3.66
B14	5.50	2.91	2.91	3.00	3.58
B7	5.53	2.83	2.85	2.90	3.53
Mean	**6.13**	**2.92**	**2.92**	**2.98**	**3.74**
Std. Dev.	**0.275**	**0.054**	**0.057**	**0.051**	**0.098**

Source: Concurrent Technologies Corporation

Table 34 shows the mean resistance across all 14 battery modules from each pack using the VDA approach at each SOC. Both batteries showed a higher internal resistance at 100 percent SOC than at 90, 80 and 70 percent state of charge, where the resistance was nearly equivalent. The difference between the mean internal resistances of both packs remained fairly consistent, with the V2G Pack always having a higher internal resistance.

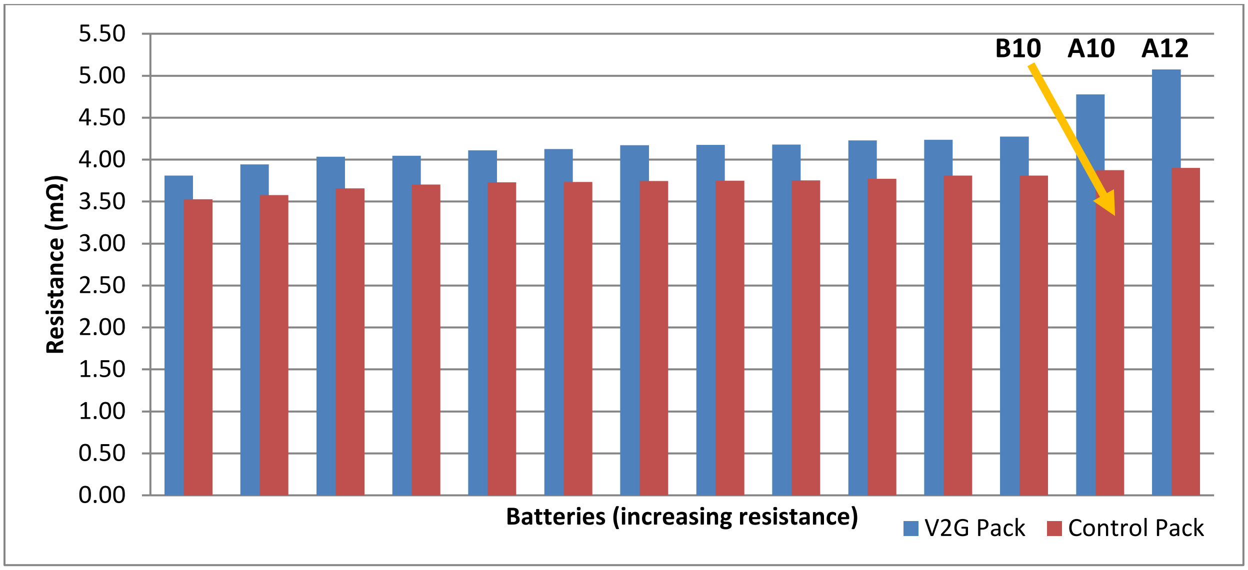
Table 34: Comparison of Internal Resistance Within Battery Packs

	Mean Resistance (mΩ)				
	100% SOC	**90% SOC**	**80% SOC**	**70% SOC**	**Battery Pack Mean**
V2G Pack	6.85	3.31	3.34	3.41	4.23
Control Pack	6.13	2.92	2.92	2.98	3.74
Difference between V2G and Control Packs	11.2%	12.5%	13.3%	13.3%	12.3%

Source: Concurrent Technologies Corporation

Figure 57 shows the distribution of internal resistance in each battery pack. The values are organized from lowest to highest internal resistance (Pareto fashion) to provide a graphical representation of trends in pack variability and magnitude. V2G Pack battery modules had greater internal resistance than Control Pack batteries in nearly all cases. Two battery modules (A10 and A12) from the V2G Pack modules exhibited noticeably more internal resistance than the other modules.

Figure 57: Comparison of Internal Resistance Between V2G and Control Packs



Source: Concurrent Technologies Corporation

BMS data captured during testing consisted of the maximum cell temperature and the individual cell voltages at each measurement interval. From these data, information such as the minimum cell voltage, standard deviation of the minimum cell voltages, mean minimum cell voltages, termination voltage and maximum cell temperatures were determined. Table 35 and Table 36 show a summary of this information.

A noteworthy observation is the termination voltage for all battery modules. The test was expected to terminate at 10.5 volts. The V2G Pack had termination voltages ranging from 10.49 to 10.97 volts, while the Control Pack had termination voltages from 10.51 to 10.58 volts. These differences in termination voltage are attributed to the variability in SOH at the cellular level. Another factor to consider when interpreting these results is the BMS sampling rate of 0.5 hertz. A possible consequence of this low default sampling rate is that some of the termination voltages shown may represent values that occurred up to 2.0 seconds before the actual termination event, which is where the lowest battery voltages would occur during the test.

Table 35: V2G Pack Cell-Level Information

Battery	Min. Cell Voltage (V)	Std. Dev. of Min. Cell Voltage (V)	Termination Voltage (V)	Capacity (Ah)	Maximum Cell Temperature (°C)
A7	2.37	0.18	10.72	112.8	43.6
A8	2.50	0.10	10.51	112.3	44.1
A14	2.50	0.12	10.52	111.7	45.4
A1	2.47	0.14	10.49	110.9	44.7
A9	2.51	0.08	10.52	110.3	44.4
A10	2.23	0.26	10.51	109.5	† 22.6
A11	2.37	0.20	10.80	106.1	46.5
A13	2.42	0.17	10.50	106.0	45.4
A6	2.37	0.20	10.78	105.6	44.4
A12	2.25	0.26	10.50	104.1	† 22.4
A2	2.36	0.23	10.61	102.3	45.4
A3	2.35	0.24	10.97	101.3	44.6
A4	2.36	0.25	10.88	100.5	43.9
A5	2.36	0.25	10.94	99.0	43.9
Mean	2.39	0.19	10.66	106.6	44.7
Std. Dev.	0.08	--	0.17	4.53	0.81

† Issue with data collection, values remained constant for this metric throughout testing.
Yellow cells were excluded from mean and standard deviation calculations.

Source: Concurrent Technologies Corporation

Table 36: Control Pack Cell-Level Information

Battery	Min. Cell Voltage (V)	Std. Dev. of Min. Cell Voltage (V)	Termination Voltage (V)	Capacity (Ah)	Maximum Cell Temperature (°C)
B1	2.45	0.14	10.51	118.6	43.8
B2	2.40	0.15	10.52	118.3	43.5
B3	2.49	0.13	10.52	117.4	43.8
B4	2.37	0.18	10.58	117.0	44.0
B5	2.39	0.17	10.51	117.0	43.0
B6	2.44	0.12	10.52	116.5	44.0
B7	2.49	0.08	10.52	116.4	43.6
B8	2.57	0.07	10.52	116.3	43.3
B9	2.54	0.06	10.51	116.1	43.2
B10	2.50	0.11	10.53	116.1	† 21.5
B11	2.45	0.13	10.52	115.9	43.3
B12	2.51	0.10	10.53	115.2	44.1
B13	2.38	0.17	10.51	115.0	44.0
B14	2.50	0.09	10.52	114.1	42.8
Mean	2.46	0.12	10.52	116.4	43.6
Std. Dev.	0.06	--	0.02	1.18	0.40

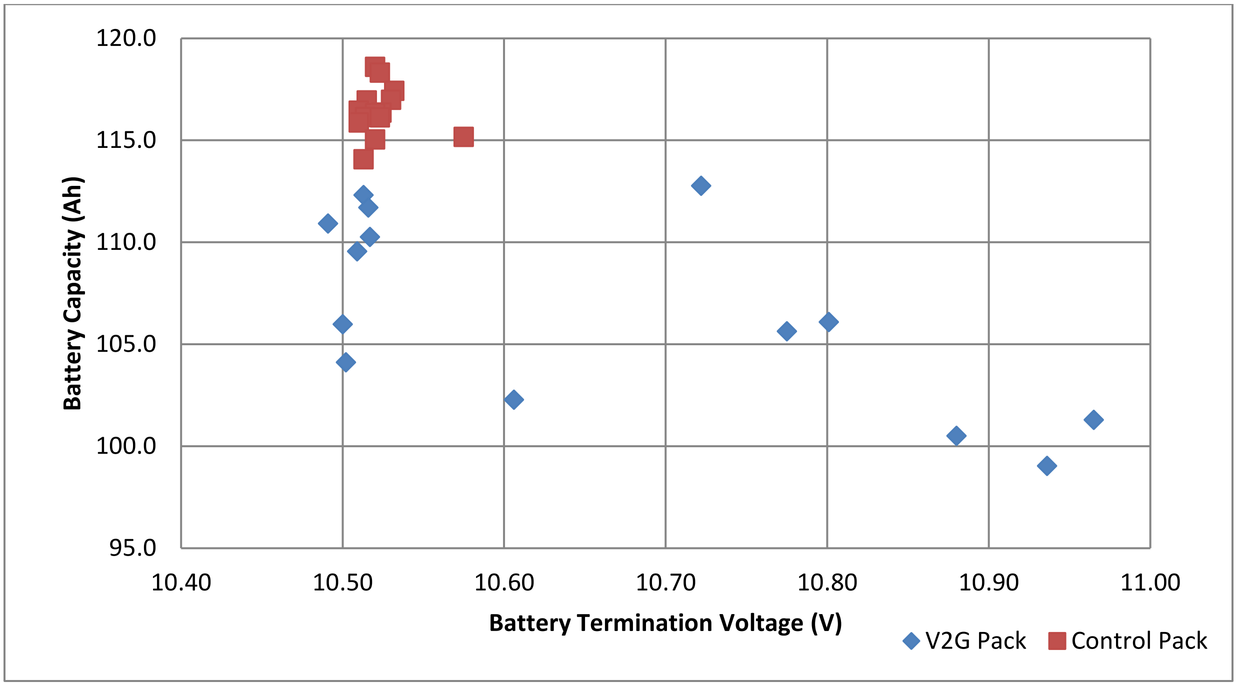
† Issue with data collection, value remained constant for this metric throughout testing.
Yellow cell was excluded from mean and standard deviation calculations.

Source: Concurrent Technologies Corporation

The measured cell temperatures for batteries A10, A12 and B10 remained constant throughout testing (approximately ambient). This likely indicated damaged internal thermocouples, which may have provided faulty data to the BMS resulting in uncertain response by the BMS as it attempted to regulate the battery. These same three batteries exhibited abnormal temperature patterns relative to the other batteries tested as noted in Table 35 and Table 36.

Summing the minimum cell voltages at the conclusion of discharge testing revealed the battery voltage at shutoff. Figure 58 shows a weak correlation between the shutoff voltage and the battery capacity, suggesting that as battery capacity decreased, the voltage shutoff limit increased.

Figure 58: Termination Voltage vs. Battery Capacity

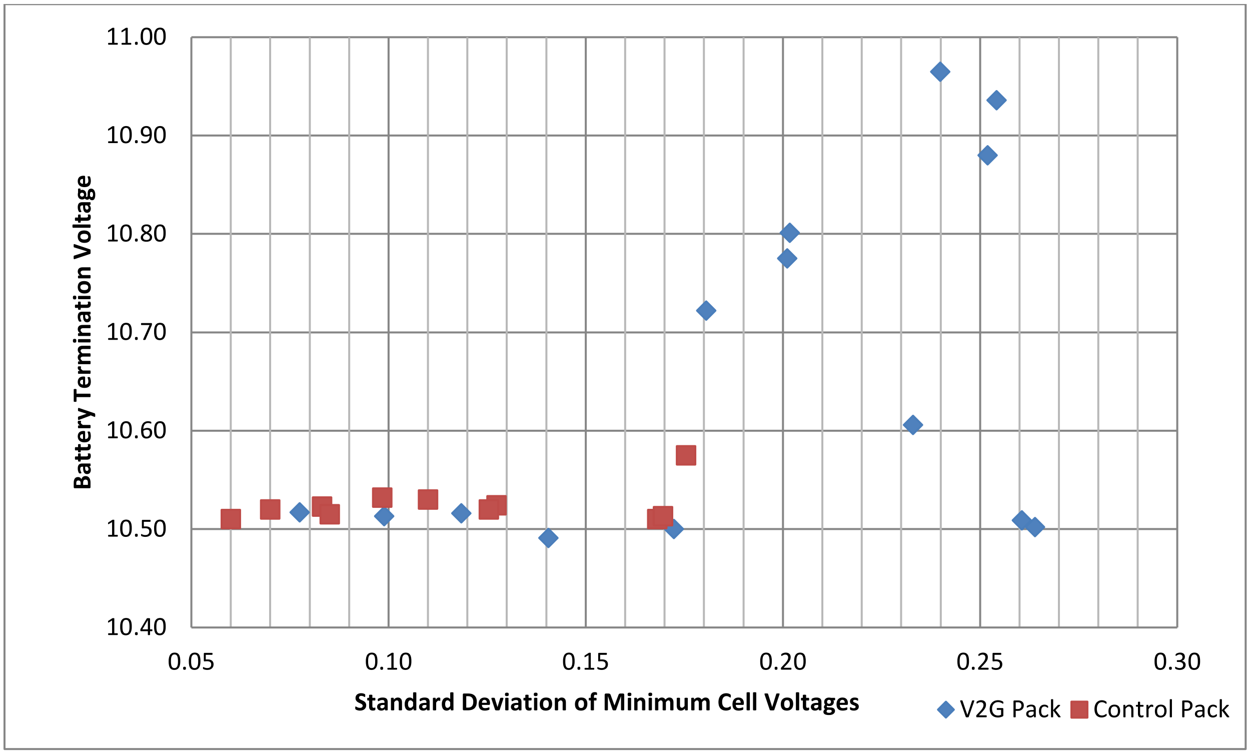


Source: Concurrent Technologies Corporation

Recognizing that the test protocol calls for discharge termination when either the battery voltage reaches 10.5 volts or a cell reaches 2.3 volts, it appears that as capacity diminishes, battery termination voltage increases because cells are reaching critically low voltages before the battery voltage reaches its shutoff condition. This points to the value of measuring cell-level battery performance as part of the categorization and selection process for second-life batteries.

The minimum cell voltages shown in Table 35 and Table 36 are not very revealing since no trends were observed in the data. However, the standard deviation of minimum cell voltages among all four cells of the battery does appear to show some discriminating factors for potential use in categorizing batteries. Generally, as the standard deviation among minimum cell voltages increased, the termination voltage increased and battery capacity decreased. This relationship between standard deviation and termination voltage can be viewed in Figure 59.

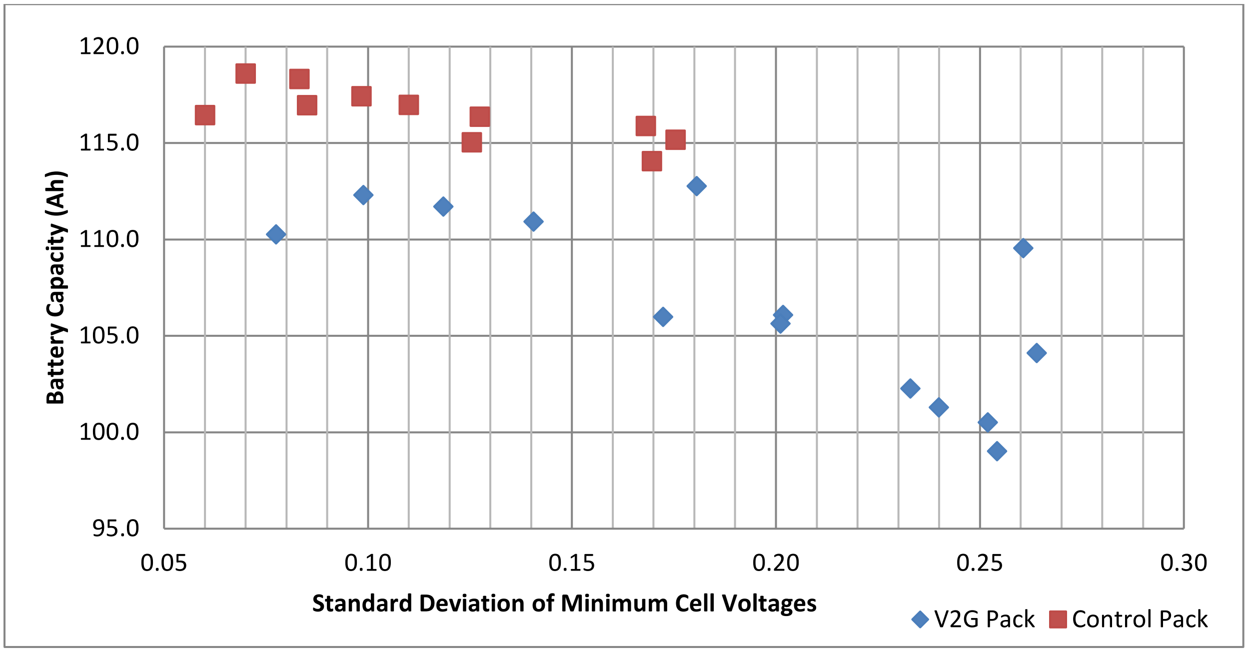
Figure 59: Termination Voltage vs. Standard Deviation of Minimum Cell Voltages



Source: Concurrent Technologies Corporation

Figure 60 shows the relationship between energy storage capacity and the standard deviation across the minimum cell voltages recorded during testing. As the standard deviation in minimum voltage across each cell within the battery increased, battery capacity decreased. As one would expect, the standard deviation across minimum cell voltages is a valuable indicator of battery condition. This observation supports the hypothesis noted earlier—as cells become more degraded, the standard deviation across the cell voltages within the pack increases until one of the cells reaches a critically low voltage that concludes testing, leaving potential energy in the less degraded cells.

Figure 60: Battery Capacity vs. Standard Deviation of Minimum Cell Voltages



Source: Concurrent Technologies Corporation

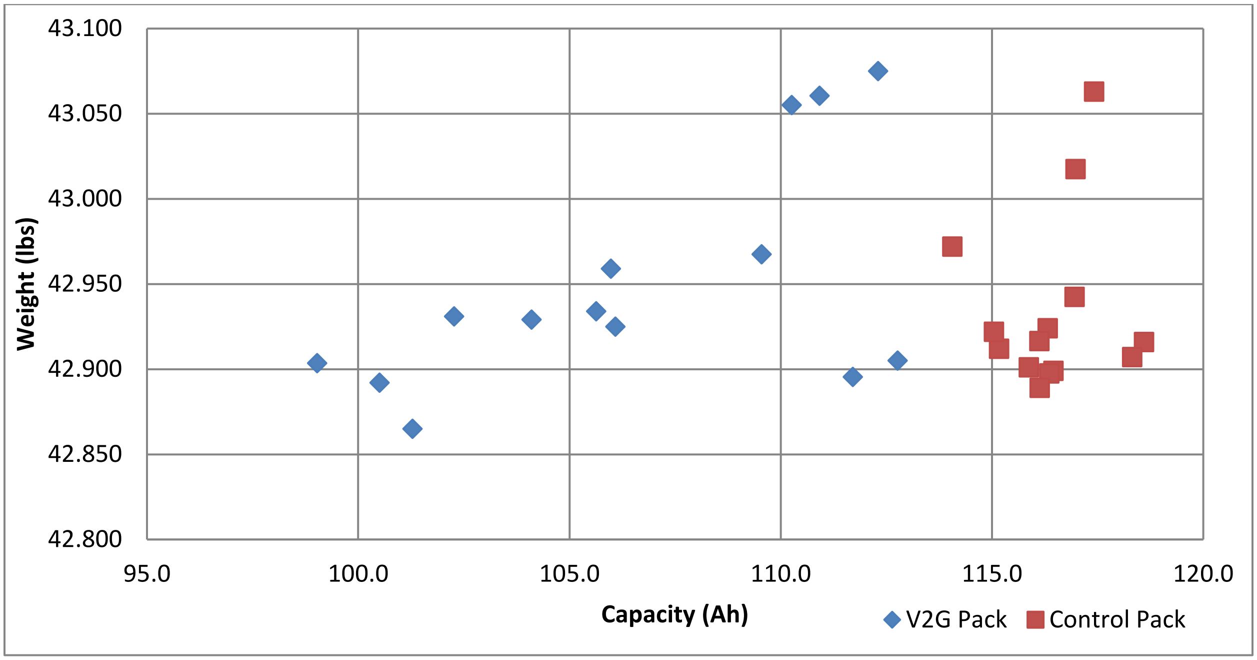
Table 37 contains the weights of the batteries measured after testing, calculated capacities and ratios of battery capacity to weight. Using these data, a correlation was sought between weight and capacity. However, no meaningful correlation between remaining battery capacity and weight was identified. Figure 61 illustrates no discernable relationship between decreasing battery weight and diminishing capacity.

Table 37: Weight Observations

Battery	Weight (lbs.)	Capacity (Ah)	Capacity/ Weight (Ah/lb.)	Battery	Weight (lbs.)	Capacity (Ah)	Capacity/ Weight (Ah/lb.)
A7	42.905	112.8	2.628	B8	42.916	118.6	2.763
A8	43.075	112.3	2.607	B7	42.907	118.3	2.758
A14	42.896	111.7	2.604	B12	43.063	117.4	2.727
A1	43.061	110.9	2.576	B10	43.018	117.0	2.719
A9	43.055	110.3	2.561	B14	42.943	117.0	2.724
A10	42.968	109.5	2.550	B9	42.899	116.5	2.715
A11	42.925	106.1	2.471	B11	42.898	116.4	2.712
A13	42.959	106.0	2.467	B2	42.924	116.3	2.710
A6	42.934	105.6	2.460	B1	42.889	116.1	2.708
A12	42.929	104.1	2.425	B6	42.917	116.1	2.706
A2	42.931	102.3	2.382	B5	42.901	115.9	2.701
A3	42.865	101.3	2.363	B4	42.912	115.2	2.684
A4	42.892	100.5	2.343	B3	42.922	115.0	2.680
A5	42.904	99.0	2.308	B13	42.972	114.1	2.654

Source: Concurrent Technologies Corporation

Figure 61: Battery Capacity and Weight Relationship



Source: Concurrent Technologies Corporation

Battery Evaluation Methods

A variety of measurements were made to determine the condition of used batteries for classifying/rating them for the most appropriate second-life application. Some test methods were time consuming in setup or data processing while other approaches were fast and revealing. Table 38 provides an overview of the tests conducted and their relative difficulty and usefulness. It also suggests various combinations of tests (i.e., methods) to determine battery condition based on resources available such as time, equipment and technical capability.

Table 38: Evaluation Methods

Test	Value	Difficulty	Method 1	Method 2	Method 3
Energy Storage Capacity	High	Low	✓	✓	✓
Battery Termination Voltage	High	Low	✓	✓	✓
Variability of Minimum Cell Voltages	High	Moderate		✓	✓
Internal Resistance	Moderate	Extensive			✓
Efficiency	Moderate	Low	✓	✓	✓
Temperatures	Minimal	High			
Weight	Minimal	Low			

Source: Concurrent Technologies Corporation

Based on our testing of a limited sample set, energy storage capacity is the leading indicator for battery health and internal resistance, efficiency and minimum cell voltage variability (i.e., standard deviation) also tend to be general indicators of condition. All three of these factors correlate with energy storage capacity, but as capacity is reduced, the correlation with minimum cell voltage variability becomes intermittent until capacity decreases substantially before the correlation resumes (see Standard Deviation of Minimum Cell Voltage column in Table 39). Higher cell-voltage variability is an indicator of a weak cell or poor cell balancing, which triggers early termination of energy delivery, thereby limiting the battery's measured capacity. This trend is most noticeable at extremes—batteries with low capacity have high variability, and batteries with high capacity have very low variability. Also, a relationship between cell-voltage variability and battery test termination voltage was observed, meaning batteries with low cell-voltage variability achieved a lower battery termination voltage whereas batteries with higher cell-voltage variability had higher termination voltages.

Test method 1 shown in Table 38 defines determination of battery condition by capacity, termination voltage and efficiency because all are very telling of battery health and can be determined by processing data from one source—the battery charge/discharge test. Efficiency is easily calculated when gathering the information necessary to calculate the battery's capacity. Capacity is a major indicator of battery degradation and can produce a coarse evaluation of the overall battery health by itself when compared to the rated capacity. Efficiency tends to follow capacity, decreasing as capacity decreases. Termination voltage is the lowest battery voltage recorded during testing. Termination voltages greater than 0.1 volt above the manufacturer-specified shutoff voltage of 10.5 volts (i.e., 10.6 volts and higher) may indicate abnormal degradation of one or more cells within the battery module, suggesting some degree of cell-level damage due to a critically low cell voltage causing a termination in testing. All three of these battery condition parameters can be obtained from the data generated by one complete test protocol execution.

Test method 2 is nearly the same as test method 1 with the addition of data retrieval from the BMS. The BMS provides voltages for the individual cells, allowing cellular voltage information to be parsed for insight into cell-level degradation by calculating the standard deviation of the minimum cell voltages throughout testing. Because the BMS is required for testing in all situations, no additional equipment is needed, only additional steps to save and process the BMS data. Test method 2 is recommended because it adds greater fidelity and understanding to battery health at the cellular level.

Test method 3 adds determination of the battery's internal resistance to the metrics discussed in the previous test methods. Internal resistance was held as the final addition to testing because it is much more time consuming to calculate. CTC wrote a Visual Basic for Applications program to collect the many pieces of information required for the final resistance calculations. Anyone interested in calculating the internal resistance for more than a few batteries would need to develop a semi-automated approach to make this calculation tractable.

External battery temperature tended to be a weak indicator of battery condition at best, with several instances where batteries with higher internal resistance had lower mean temperatures than batteries with lower internal resistance. Due to inconsistencies in trends and the significant level of effort required to acquire this information, external module case temperature is not recommended as a battery condition indicator.

Grading Methods

Understanding the ultimate goal was to group like batteries, two approaches were developed—a single all-encompassing score and a categorical assessment. These two approaches allow customers to purchase general purpose, and potentially lower quality batteries for less-demanding needs (i.e., backup power to a home) or specific higher quality batteries meeting specific, more-demanding requirements (i.e., reuse to help manage the grid).

Grading Method 1: Single Representative Score

This grading method determines a single relative score that incorporates measurable battery characteristics to provide insight into overall battery health by combining both general performance and cellular-level information. Equation 16 details the approach to computing a single comprehensive score with greater weight being given to the most critical parameters. Higher scores indicate healthier batteries.

Equation 16: Single Score

$$Score = \left(\frac{Measured\ Capacity}{Internal\ Resistance}\right)\left(\frac{Nameplate\ Shutoff\ Voltage}{Recorded\ Termination\ Voltage}\right)(Average\ Efficiency)$$

Table 39 reviews the most significant battery condition parameters and the final score for each battery generated by Equation 16. The color formatting in Table 39 highlights trends and abnormalities in values. Green indicates the most desirable performance, while red cells indicate lower performance.

Notice that scores between the two battery packs are distinguishable when sorted by score. Ideally, a battery's first-life application and use profile is known and considered during its evaluation, so the score obtained from Equation 16 provides results that correlate with expected battery characteristics. Because a battery's usability is driven by termination voltage, the manufacturer-specified shutoff voltage appears in the numerator so, when a battery reaches termination voltage prematurely due to a low-cell voltage alarm, the battery score is penalized.

By examining the measured battery parameters and their relative scores calculated by Equation 16, the battery testers may judiciously choose classes or score ranges for battery classification based on their target market or application.

Table 39: Results and Final Score Summary for Single-Score Method

Battery	Mean Capacity (Ah)	Std. Dev. of Min. Cell Voltage (V)	Termination Voltage (V)	Mean Efficiency (%)	Internal Resistance (mΩ)	Final Score
B7	118.32	0.08	10.52	93.5	3.53	**31.3**
B14	116.96	0.09	10.52	93.3	3.58	**30.4**
B8	118.60	0.07	10.52	93.5	3.66	**30.3**
B1	116.13	0.14	10.51	93.3	3.70	**29.2**
B9	116.45	0.06	10.51	93.4	3.73	**29.1**
B2	116.32	0.15	10.52	93.3	3.74	**29.0**
B6	116.12	0.12	10.52	93.4	3.75	**28.8**
B5	115.87	0.17	10.51	93.4	3.75	**28.8**
B11	116.36	0.13	10.52	93.4	3.77	**28.8**
B12	117.42	0.10	10.53	93.4	3.81	**28.7**
B3	115.04	0.13	10.52	93.3	3.74	**28.6**
B10	116.98	0.11	10.53	93.2	3.87	**28.1**
B4	115.17	0.18	10.58	93.2	3.81	**28.0**
B13	114.06	0.17	10.51	93.2	3.90	**27.2**
A14	111.70	0.12	10.52	93.0	3.81	**27.2**
A7	112.77	0.18	10.72	93.1	3.94	**26.1**
A8	112.30	0.10	10.51	93.0	4.03	**25.9**
A1	110.92	0.14	10.49	92.7	4.05	**25.4**
A9	110.26	0.08	10.52	92.8	4.11	**24.8**
A13	105.98	0.17	10.50	92.4	4.13	**23.7**
A11	106.09	0.20	10.80	92.8	4.18	**22.9**
A6	105.63	0.20	10.78	92.4	4.18	**22.8**
A2	102.27	0.23	10.61	92.5	4.17	**22.5**
A3	101.28	0.24	10.97	92.5	4.23	**21.2**
A4	100.51	0.25	10.88	92.1	4.23	**21.1**
A10	109.55	0.26	10.51	92.0	4.78	**21.1**
A5	99.02	0.25	10.94	92.1	4.28	**20.5**
A12	104.10	0.26	10.50	91.6	5.08	**18.8**

Source: Concurrent Technologies Corporation

Grading Method 2: Categorical Assessment

This grading method allows for greater fidelity in battery classification. This approach allows the battery evaluator to most accurately group batteries and affords customers the ability to select batteries for their unique application where one or several categories of battery health are of lower importance and therefore allow for a greater range of battery health measures. In the example of a homeowner purchasing batteries for peak load shaving or backup power, batteries with higher capacities, but low efficiencies and/or high internal resistances may be acceptable because the homeowner could charge batteries during non-peak hours when electricity costs are lower.

For example, battery A12 in Table 39 has a relatively high capacity, very low efficiency and high internal resistance. Using the arbitrary categorical rating system identified in Table 40, this battery would be classified as ADADD, placing it in the recycle class (relative to grid application requirements) despite its relatively high capacity and low termination voltage. However, this battery could potentially serve a second-life application for a homeowner as described above.

Table 40 shows the recorded values for each battery health category measured and found to be of use in determination of battery health. Each category was ordered from highest performance to lowest performance. Using manufacturer-specified values where possible to set a standard for comparison, arbitrary ranges for each parameter were developed to define performance for the measured group of batteries. Ultimately, unique ranges for each battery type may be defined by battery type and market requirements. Table 40 serves as an example of one such set of rating scales.

Table 40: Example of Relative Categorical Assessment

		Mean Capacity (Ah)	Std. Dev. of Min. Cell Voltage (V)	Termination Voltage (V)	Mean Efficiency (%)	Internal Resistance (mΩ)
		118.60	0.06	10.49	93.5	3.53
		118.32	0.07	10.50	93.5	3.58
		117.42	0.08	10.50	93.4	3.66
		116.98	0.08	10.51	93.4	3.70
		116.96	0.09	10.51	93.4	3.73
		116.45	0.10	10.51	93.4	3.74
		116.36	0.10	10.51	93.4	3.74
		116.32	0.11	10.51	93.3	3.75
		116.13	0.12	10.51	93.3	3.75
		116.12	0.12	10.52	93.3	3.77
		115.87	0.13	10.52	93.3	3.81
		115.17	0.13	10.52	93.2	3.81
		115.04	0.14	10.52	93.2	3.81
		114.06	0.14	10.52	93.2	3.87
		112.77	0.15	10.52	93.1	3.90
		112.30	0.17	10.52	93.0	3.94
		111.70	0.17	10.52	93.0	4.03
		110.92	0.17	10.52	92.8	4.05
		110.26	0.18	10.53	92.8	4.11
		109.55	0.18	10.53	92.7	4.13
		106.09	0.20	10.58	92.5	4.17
		105.98	0.20	10.61	92.5	4.18
		105.63	0.23	10.72	92.4	4.18
		104.10	0.24	10.78	92.4	4.23
		102.27	0.25	10.80	92.1	4.23
		101.28	0.25	10.88	92.1	4.28
		100.51	0.26	10.94	92.0	4.78
		99.02	0.26	10.97	91.6	5.08
Rating	**Specification**	**138**		**10.5**		**5 Max**
A	**Very Good**	110	0.10	10.55	94	3.75
B	**Acceptable**	104	0.15	10.65	93	4.00
C	**Poor**	97	0.20	10.75	92	4.50
D	**Recycle**	90	0.25	10.85	91	4.75

Source: Concurrent Technologies Corporation

Results and Discussion

As part of this task, options were explored for defining second-life applications for used vehicle traction batteries. Several options from remanufacturing, repurposing and recycling were discussed. Potential applications and benefits were identified and documented. Several challenges were identified including cost competitive energy storage technologies, validated reliable and safe operations, equitable regulatory environment and industry acceptance.

A requirements document for the design of an energy storage system using second-life batteries was drafted. The grid electrical interconnection, operating characteristics and technical requirements were defined.

A preliminary design concept for second-life battery applications based on these technical requirements was generated. The objective of this design was to integrate groups of different battery chemistries and sizes whose total capacity yielded a 1-MW system to meet requirements for AS.

A DoC diagnostic best practices and protocol was developed. This included a three-phase approach: 1) Preliminary Battery Evaluation, 2) Battery Characterization and 3) Grading. Testing was performed on battery modules from an earlier laboratory testing task. Module capacity test results were consistent with what was expected based on the test data from the packs. These battery modules were used in a nearly equivalent manner based on the controlled testing (same drive profile) that was performed during laboratory assessments on the V2G and Control Packs. However, it can be expected that with the thousands of different batteries currently in EV use today from different manufacturers, and different use scenarios, there will be a broader range of battery conditions found for any future large-scale battery reuse effort. With broader condition distributions will come a greater need to group similar battery modules and cells to optimize reuse.

Repurposing used EV batteries for new applications is in its infancy. Testing and grouping these batteries for optimum reuse is only one step in the process. Implementation of any comprehensive reuse program must ensure repurposed batteries are safe to use and provide economical value to all affected parties. Therefore, the supply chain from first use through any secondary use to final recycling must be managed to ensure a safe and economical market, ultimately lowering the overall EV total ownership cost.

In closing, UL has seen the need for a standard to evaluate these batteries for second use and is developing a Standard for Evaluation for Repurposing Batteries, ANSI/CAN/UL 1974. This preliminary standard addresses construction, examination, performance, packing and shipment, markings and instructions focused on the process for repurposing batteries. The testing and data can provide insight to battery manufacturers as they review and become compliant with the UL standard.

CHAPTER 6:
Summary and Conclusions

LAAFB Field Demonstration

Based on the DoD demonstration, V2G technology and implementation is in its infancy and lags behind PEV technology. V2G market participation has been most successful when considered as part of the original design of commercial EVs, as with the LEAF sedan manufactured by Nissan. The primary EV design feature that can benefit the V2G market is the use of bi-directional charging stations. A majority of the equipment and components required for this V2G demonstration were prototypes, which is expected to progress through the product development process and be improved based on lessons learn.

The demonstration at LAAFB showed two primary use scenarios for PEVs relative to participation in V2G market opportunities. Some vehicles, such as the Nissan LEAFs, were utilized primarily for low-mileage day trips, where the vehicle was typically driven to a single location and parked for most of the day; this is similar to commuter usage by the general population. Other vehicles such as the VIA vans and the Phoenix shuttle were continuously used for stop-and-start transit applications. Commuter usage driving missions resulted in a low rate of battery degradation. Use of such commuter vehicles in V2G activities, while reducing the potential life of the batteries, will, in many cases, not alter the vehicle’s useful life, as the vehicle will need to be replaced before the batteries need to be changed. Battery degradation specific to any usage (driving, V2G, SOH) could not be quantified using data from the field demonstration (based on previous use, usage variation among vehicles and the relatively short duration of the test period).

Based on the data from the LAAFB demonstration, all vehicles experienced a large amount of idle time where V2G participation may be practical. If properly managed, a mixture of EVs, some dedicated for short-duration, commuter-like trips and some for nearly continuous use, will be practical for many commercial fleets. Use of those assets required for short-duration, commuter-like trips may be most amenable for use in V2G operation. Managing the use of these vehicles relative to the demands of a V2G market is critical to the smooth operation of both the grid and the vehicle fleet.

Laboratory Research, Testing and Analysis

The laboratory testing simulated a very aggressive driving profile on two identical battery packs with one of those packs (V2G Pack) also simulated V2G market participation profile. These were notably more aggressive than actual observations made during the field demonstration at LAAFB where “Unknown” (vehicle disconnected from EVSE and turned off) makes up a high percentage of vehicle time even for heavily utilized vehicles such as the Phoenix shuttle.

Under these aggressive conditions, the V2G Pack had capacity reduction of 25 percent over rated capacity, while the Control Pack had a capacity reduction of just 16 percent. On a simplified total energy basis, the rate of degradation for both battery packs was nearly identical. However, when accounting for operating temperature and second-order effects of time, the corrected rate of degradation was found to be less by approximately 19 percent for the V2G Pack relative to the Control Pack. Therefore, the authors conclude that daily V2G operations do not cause any greater degradation to PEV batteries (on a total energy basis) beyond that experienced during drive cycles like those simulated in the laboratory setting.

Modeling Simulation and Analysis

CTC determined the BLAST-S Lite tool has all the input selections necessary to explore battery degradation effects of custom battery use profiles. However, the software was designed for stationary applications using NCA batteries and correlating simulation results for driving and V2G will require engagement from NREL to confirm understanding of the fundamental basis of this software. Further development by NREL for this application should focus on expanding the battery chemistries available within the software and the profile size handling capability. Combining BLAST-V and BLAST-S could provide the simulation results expected. The battery use profiles that CTC created during laboratory testing can be used to test future iterations of NREL software. Use of established battery models, rather than experimental or newly developed battery models, is recommended for future battery studies.

Second-Life Battery Applications

Given the large increase in the number of EVs starting in approximately 2010 and given the planned life of 15 years for the PEV batteries, California still has some time to plan and implement strategies for beneficial reuse of EV batteries. Without a plan and the associated government policies in place before 2025, many reuse opportunities will be lost.

CTC investigated and drafted requirements for the design of an energy storage system using second-life batteries. A preliminary design concept for second-life battery applications based on technical requirements assembled under this agreement. This design concept proposed methods to integrate groups of different battery chemistries and sizes totaling a 1-MW system to meet requirements for AS.

A determination of condition protocol was developed with an associated scoring system that combines measured capacity, internal resistance, recorded termination voltage and battery efficiency appears to offer a simple and inexpensive method to judge the overall health of used batteries. This scoring system is useful for selecting groups of used batteries of similar health. However, the requirements of the intended application may require alternative scoring methods using the most appropriate subset of these measurements to ensure the maximum number of batteries are effectively used in second-use applications.

Benefits to California

This project supported California’s Alternative and Renewable Fuel and Vehicle Technology Program and Executive Order B-16-2012 zero-emission vehicles goals by generating and analyzing data to better understand vehicle-to-grid technologies to achieve the state’s climate change policies. This project benefited significantly from collaboration and coordination with the largest Department of Defense vehicle-to-grid demonstration project to explore economic value of aggregated plug-in electric vehicle storage and ancillary services to the California grid. Through the execution of this project, battery degradation due to vehicle-to-grid applications and potential for repurposing these batteries in second-life applications were investigated. The data presented in this report are useful for developing a compensation strategy for clients willing to offer their assets for use in a vehicle-to-grid application and clients looking to repurpose used electric vehicle batteries.

Specific benefits to California included:

- Developed a detailed understanding of the following aspects of V2G:
    - The use patterns of a real-world V2G fleet, the current state of V2G technologies and the factors that influenced participation in CAISO's frequency regulation ancillary services market
    - The battery degradation associated with V2G activities, as compared to other usage and environmental factors
    - The current state of V2G modeling simulation and analysis tools and their ability to predict degradation based on specified usage profiles.
- Facilitated the repurposing of electric vehicle batteries that are no longer suitable for transportation purposes (70 to 80 percent capacity remaining) in second-life applications as a stationary energy storage resources for California utilities through the following activities:
    - Prepared a preliminary design concept for the packaging electric vehicle batteries for second-life large-scale, stationary storage applications
    - Developed a determination of condition diagnostic protocol for evaluating a vehicle battery's suitability for second-life applications.
- Supported California Vehicle-Grid Integration Roadmap Track 3, "Support Enabling Technology Development" through research, development and demonstration:
    - Procured vehicle batteries in support of the DoD V2G demonstration at LAAFB and funded data collection and analysis activities undertaken for the demonstration
    - Tested performance of vehicle-grid integration enabling technologies
    - Ensured results are published for public consumption
    - Identified additional research gaps for further study.

This project provided an improved picture of a large-scale V2G implementation. No catastrophic impact to vehicle batteries was identified based on V2G testing performed under this effort. California can utilize the information from this report to define long-term PEV strategies, proactively working with PEV and EVSE vendors to determine their strategies for bi-directional charging over the next decade. As a proof-of-concept, this project demonstrates that barriers to large-scale V2G implementation are technical and short term. The next steps will largely be dependent on convincing original equipment manufacturers to continue to evolve these products in support of California's growing PEV fleet and growing ancillary services market.

Acronyms, Abbreviations and Symbols

#	Number
%	Percent
~	Approximately
<	Less than
<=	Less than or Equal to
>	Greater than
°C	Degrees Celsius
°F	Degrees Fahrenheit
A	Ampere
AC	Alternating Current
AGC	Automated Generation Control
Ah	Amp-Hour
amp	Ampere
ANSI	American National Standards Institute
ARFVTP	Alternative and Renewable Fuel and Vehicle Technology Program
AS	Ancillary Services
ASRP	Ancillary Service Requirements Protocol
BLAST	Battery Lifetime Analysis and Simulation Tool
BLAST-S	Battery Lifetime Analysis and Simulation Tool-Stationary
BLAST-V	Battery Lifetime Analysis and Simulation Tool-Vehicle
BMS	Battery Management System
C	Discharge Capacity (kWh)
California ISO	California Independent System Operator
CBC	California Building Code
CCM	Charge Control Module
CFC	California Fire Code
CLEE	Center for Law, Energy & the Environment
CONEX	Container Express
CSE	Center for Sustainable Energy
CSV	Comma-Separated Values
CTC	Concurrent Technologies Corporation
D	Depth of Discharge (%)
DAM	Day Ahead Market
DAQ	Data Acquisition
DC	Direct Current
DNP	Distributed Network Protocol
DNV-GL	Det Norske Veritas--Germanischer Lloyd
DoC	Determination of Condition
DoD	Department of Defense
DOD	Depth of Discharge
DOE	Department of Energy

E	Energy Efficiency (%)
EDR	Electrochemical Dynamic Response
EIS	Electrochemical Impedance Spectroscopy
EMS	Energy Management System
EOD	End of Drive
EPA	Environmental Protection Agency
ESS	Energy Storage System
E_T	Total Energy (MWh)
EV	Electric Vehicle
EVAOS	Electric Vehicle Add-On Systems
EVI	Electric Vehicles International LLC
EVSE	Electric Vehicle Supply Equipment
FMS	Fleet Management System
GWh	Gigawatt-Hours
HMI	Human Machine Interface
I	Current
ICE	Internal Combustion Engine
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
K	Cycle Count
km	Kilometer
kph	Kilometers per Hour
kW	Kilowatt
kWh	Kilowatt-Hour
LAAFB	Los Angeles Air Force Base
lb.	Pound
$LiFeMgPO_4$	Lithium Iron Magnesium Phosphate
$LiFePO_4$	Lithium Iron Phosphate
$LiNiCoAlO_2$	Lithium Nickel Cobalt Aluminum Oxide
mi	Mile
mpg	Miles per Gallon
mph	Miles per Hour
MW	Megawatt
MWh	Megawatt-Hour
mΩ	Milliohms
N/A	Not Applicable
NCA	Nickel Cobalt Aluminum
NCC	Nameplate Capacity Comparison
NEC	National Electric Code
NEMA	National Electrical Manufacturers Association
NRC	Nuclear Regulatory Commission
NREL	National Renewable Energy Laboratory

NRTL	Nationally Recognized Testing Laboratory
OBDC	On-Board Data Collection
OB-EVI	On-Base Electric Vehicle Infrastructure
OEM	Original Equipment Manufacturer
OSHA	Occupational Safety and Health Administration
PCBA	Printed Circuit Board Assembly
PEV	Plug-in Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
PLC	Programmable Logic Controller
pm	Post Meridian
PPS	Princeton Power Systems
R^2	Statistical measure of how close the data are to the fitted regression equation
RDT&E	Research, Development, Test and Evaluation
REEV	Range Extended Electric Vehicle
REM	Regulation Energy Management
Ri	Internal Resistance
RMS	Root Mean Square
ROC	Rate of Change
RTM	Real Time Market
SCADA	Supervisory Control and Data Acquisition
sec	Seconds
SEI	Solid Electrolyte Interphase
SL-VBP	Second-Life Vehicle Battery Packs
SOC	State-of-Charge
SOH	State of Health
t	Time (days from April 27, 2015)
TCP/IP	Transmission Control Protocol/Internet Protocol
TMS	Thermal Management System
T_P	Mean Pack Temperature (°C)
U	Voltage during Internal Resistance Testing
U.S.	United States
UCSD	University of California San Diego
UDDS	Urban Dynamometer Driving Schedule
UL	Underwriters Laboratories Inc.
USB	Universal Serial Bus
V	Volt
V2G	Vehicle-to-Grid
VDA	Verband der Automobilindustrie
VDC	Volts Direct Current
VIA	VIA Motors
vs.	Versus
W	Watt

Wh	Watt-Hour
WMG	WMG Innovative Solutions

Appendix A:
Battery Related Terminology – Definitions of Terms

Several technical terms are used throughout this document to describe the battery test materials procured under this effort. They are defined as follows.

Battery Management System (BMS): This is the system that manages the battery by monitoring its state of charge, controlling charge or discharge rates, and balancing the load on the battery evenly between individual cells. BMS units are typically proprietary technology that is custom-built and programmed for PEV batteries by the vehicle vendor. For some of the batteries, the BMS is included as part of the procured battery material, and in other cases it is part of the vehicle and not included as part of the battery.

Capacity: A measure of the charge stored by the battery, measured in this document in kilowatt-hours (kWh). A battery's capacity degrades over time as it is charged and discharged.

Cells: The smallest energy-containing unit of a battery. Multiple cells are connected in each battery to achieve the desired performance parameters.

Cycle: In this document, a "cycle" without qualifier refers to "deep cycles" in which a cell is discharged to less than half of its total energy, then recharged to full capacity. There are also "shallow cycles" in which the battery is discharged by only a small amount before being recharged.

Depth of Discharge (DOD): The percentage of the battery's total energy which is discharged. Depth discharge is used to distinguish deep and shallow cycles.

Second-Life: Some PEV vendors recommend replacement of vehicle batteries during the vehicle's working life. This is done when the battery capacity drops and the battery stores less energy, reducing the vehicle's range. Even when the vehicle range has dropped low enough to mandate replacement, these batteries will typically have many kWh of capacity remaining. By transitioning the battery to become a stationary energy storage system rather than scrapping/recycling it, some of the original cost of the battery can be recovered. This is the "second life" of the battery.

Thermal Management System (TMS): Temperatures outside a battery's recommended operating range can affect performance and battery life. Thermal management systems are used to control the battery temperature. For some of the batteries, the thermal management system is included as part of the procured battery material. In other cases, it is part of the vehicle and not included as part of the battery.

Vehicle-to-Grid (V2G): Using a modified charging system and control software, energy flow between a PEV battery and the electrical grid can be bi-directional. This allows the grid to discharge from the battery during moments of high demand and charge the battery during periods when demand is lower than the power produced within the grid. By selling this capacity to utilities, V2G can ameliorate the cost of PEVs.