**Public Interest Energy Research (PIER) Program**

**FINAL PROJECT REPORT**

# Long Term Endurance Testing of Distributed Energy Storage Systems (DESS)

Prepared for: California Energy Commission

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# PREFACE

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Long Term Endurance Testing of Distributed Energy Storage Systems is a deliverable for the California Energy Commission contract number 500-10-043 conducted by the University of California, San Diego. The information from this project contributes to PIER's Renewable Energy Technologies Program.

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# ABSTRACT

Deployment of energy storage will be an important factor that will enable reliance on renewable energy generation as an efficient, reliable, cost effective source of generation in California. Much of the renewable generation that has been and is continuing to be installed are small roof top systems on residential and commercial buildings. This distributed renewable resource generation (DER) will also require distributed energy storage systems (DESS) to ensure stable distribution voltages and defer distribution system upgrades by reducing line loadings. It is also anticipated that DESS will be able provide "behind the meter services" for commercial and residential customers. The applications for DESS could include peak shifting, demand reduction, emergency backup, as well as ancillary services.

Distributed energy storage is a relatively new technology, and little is known about its expected long term performance characteristics. UCSD has been testing distributed energy storage on its campus and has been monitoring the performance over the last 3 years. UCSD as part of task 3.2 of the CEC contract 500-10-043 has developed this report to describe the results of this performance monitoring of DESS and the expected long term performance.

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# EXECUTIVE SUMMARY

UCSD has been field testing a few distributed energy storage systems (DESS) over the last 3 years. Battery chemical energy storage for supporting integration of renewable generation is relatively new, and distributed smaller energy storage systems for commercial and behind the meter applications has little long term performance history. UCSD installed one of the first DESS in the US in early 2011, and thus has some of the longest collected performance information to-date.

This report documents the results of testing of two separate DESS over a period of 3 years for various use applications. The use applications considered include:

- Smoothing of renewable intermittency
- Peak Load Reduction using stored solar PV generation
- Energy Arbitrage
- Frequency Regulation
- Demand Charge Management
- Regulation Energy Management

One system consisted of a 30 kW / 30 kWh DESS supplied by Sanyo/Panasonic and is integrated with 30 kW of roof top PV solar, the project was interfaced with UCSD's solar forecasting system, and testing was focused on firming renewables. This system was one of the first distributed energy storage systems (DESS) integrated with PV solar and installed in California, in fact at the time this was one of the first DESS installed in the US, and thus has been in operation collecting the most data for DESS. The control algorithms developed for this DESS were developed to accept solar forecasting information and command the energy storage system to store PV solar generated when it is generated during off peak hours, and discharge energy during on peak hours to reduce the local load and peak demand requirements, as well as smoothing the impact of renewable intermittency.

The second DESS system consisted of 125 kW / 65 kWh of energy storage utilizing four used PEV battery packs. The control system for this DESS included demand charge management (DCM) and Regulation Energy Management (REM).

Results of this testing indicate that the overall DESS performance and life expectancy is highly dependent on the use case applications that are implemented for the particular application of the DESS and the performance is also highly affected by the design and control of the battery management and power management systems employed for the DESS.

# CHAPTER 1
# INTRODUCTION

Renewable resources will increasingly be relied upon to provide a clean source of energy, unfortunately renewable generation sources are also highly variable and depend upon changing weather conditions. Energy storage would help store energy produced by renewable generation sources and release it later when needed to, in effect, make renewable resources a more firm dispatch able generation source. However many questions need to be resolved regarding energy storage, such as cost effectiveness, reliability, safety, and life expectancy. UCSD has been testing Distributed Energy Storage Systems for the last three years to determine the expected performance. This report will discuss some of the results of this testing and some of the concerns that have been identified with DESS and possible recommendations on possible solutions.

# CHAPTER 2:
# DESS Test Projects

## 2.1 Sanyo/Panasonic 30 kW / 30 kWh DESS

In early 2011 UCSD installed its first 30 kW/ 30 kWh lithium-ion energy storage system integrated with 30 kW of roof top PV solar. The 30 kW/ 30 kWh energy storage system is located at the La Jolla Playhouse UCSD, and it is outdoors and enclosed in a 20 ft. modified storage container. This lithium-ion energy storage system is integrated with 30 kW of roof top PV solar, the project was interfaced with UCSD's solar forecasting system, and testing was focused on firming renewables, smoothing of intermittency, and peak load shifting use cases. This system was one of the first distributed energy storage systems (DESS) integrated with PV solar and installed in California, in fact at the time this was one of the first DESS installed in the US, and thus has been in operation collecting the most data for DESS. Figure 1 shows the schematic summary of the DESS and how it is integrated with PV solar and local distribution customer load.

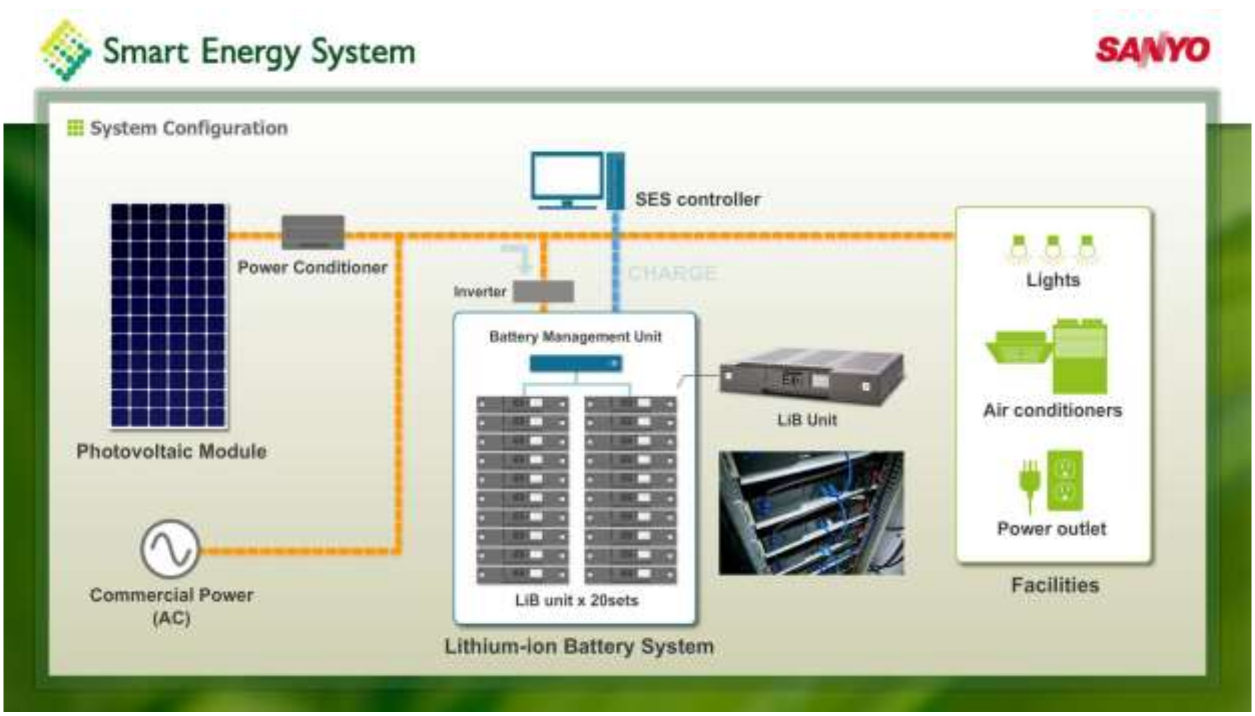


**Figure 1 Sanyo DESS System Summary**

The DESS utilizes lithium-ion batteries that are packaged in modules; each module contains 312 standard P18650 batteries. Each module is rated at 1.6 kWh, there are a total of 20 modules in the container, see picture below in Figure 2. The DESS is connected to the same AC power system as the 30 kW PV solar system and the PV solar inverter and DESS inverter are designed to work in concert through a local control and monitoring system. The 30 kW

PV solar system is located on the roof of the adjacent Mandel Weiss Theater and consists of 150 Sanyo panels.

**Figure 2 Sanyo DESS battery system**

**Figure 3 Sanyo PV Solar Panels**

The DESS controller is designed to control charge and discharge of the batteries to stabilize the power use and reduce peak. Also energy arbitrage has also been utilized to charge the DESS during off peak hours when energy costs are lower, and discharged later to meet theater peak load requirements.

### 2.1.1 Energy Cost minimization and Arbitrage using DESS

A control algorithm was developed to purchase power during off peak periods when energy cost production is lower. A separate control algorithm was developed to accept solar forecasting information and command the energy storage system to store PV solar generated when it is generated during off peak hours, and discharge energy during on peak hours to reduce the local load and peak demand requirements. Figure 4 below shows an example of this operation.

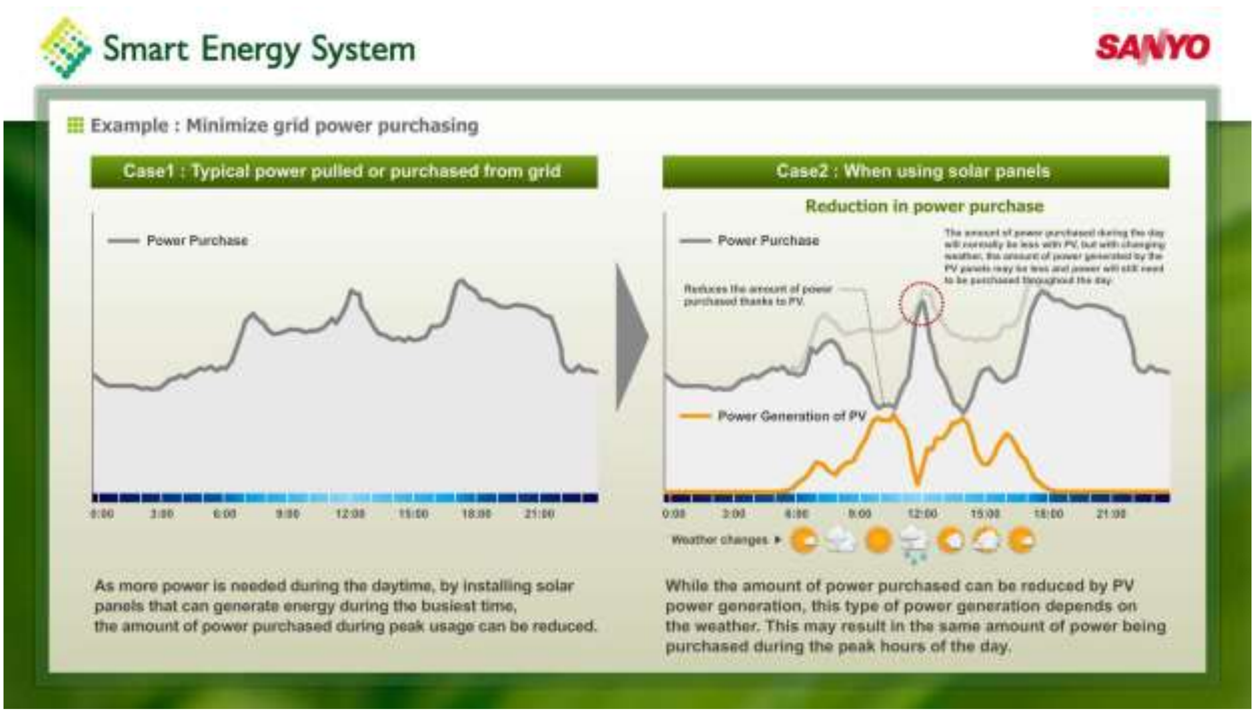


**Figure 4 Control optimization to minimize energy costs using DESS**

### 2.1.2 Smoothing of PV Solar Intermittency and minimization of impact on the electric distirbution system using DESS

The impact of high levels of PV penetration on the distribution system has become a concern to utility operations and customer power quality. One of the major concerns is the potential impact of the rapid fluctuations of distribution voltages and line loading caused by the intermittency of PV due to the passing of clouds.

A control algorithm was developed for monitoring the PV roof top power production and control of the DESS charge and discharge to smooth out the intermittency with the goal of improving distribution system performance. This control concept was tested using the Sanyo DESS and adjacent rooftop PV. Figure 5 below shows an example of how this type of control worked.

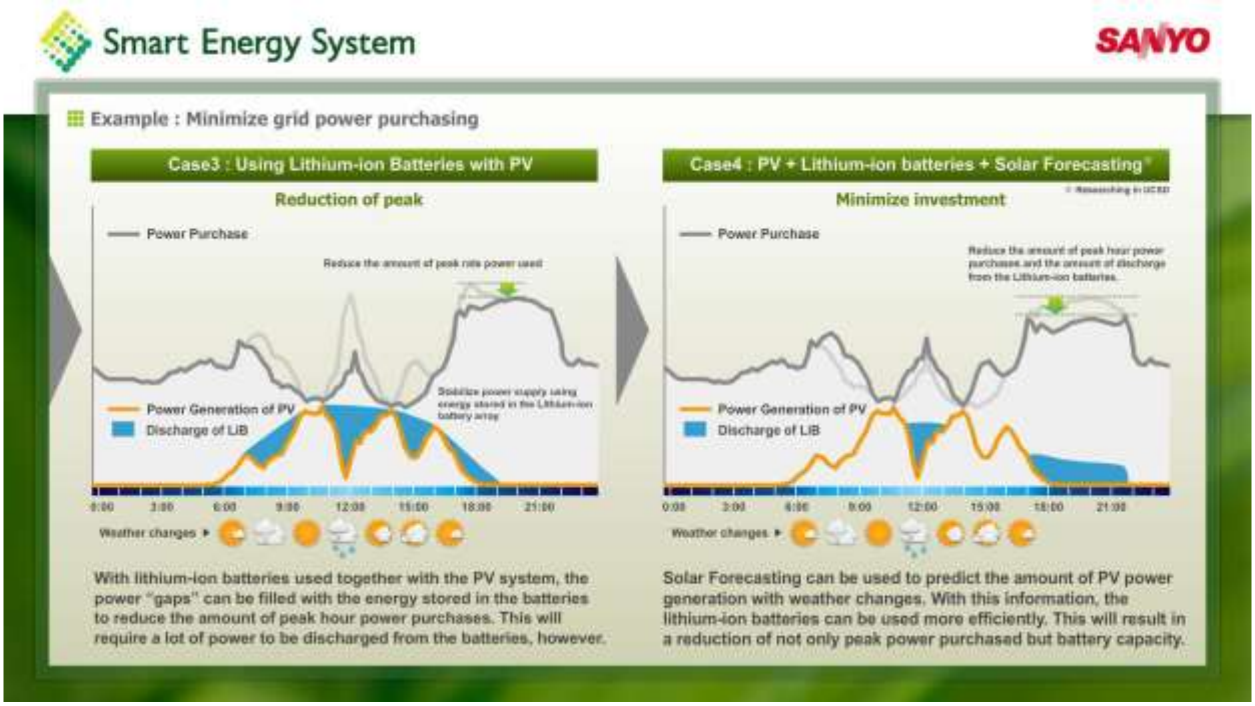


**Figure 5 Smoothing of PV Intermittency using DESS**

### 2.1.3 Battery Management Control design to maximize battery life expectancy

The management of the individual batteries and modules is important to ensuring long battery life for long endurance energy stationary energy storage applications. The Sanyo DESS battery management control unit (BMU) was designed to monitor and calculate in real time the voltage and temperature of each individual lithium-ion battery cell and make adjustments to optimize performance. The BMU is designed to manage the individual battery modules and cells as one large integrated energy storage system with optimized performance. The goal of the BMU control algorithms is to ensure long battery life. Based on continually monitoring voltage, current and temperature received data from the individual cells the control system estimates the life span of each cell and optimizes the performance of the battery system. The DESS also has a battery switching unit (BSU) that allows switching individual battery modules on and off and reconfiguring the overall system as needed to improve overall performance.

In addition the DESS has a Power Management Unit (PMU) which manages the discharge and charge rates of the overall battery system. The PMU has the following functions, the main purpose of the PMU is to ensure that the battery energy storage system operates within safe limitations, and acts mainly as protection functions.

1. **Battery status management**

・Battery module total and individual cell overvoltage detection / charge and discharge current detection / temperature detection.

2. **Charge management**

・Charge permission / Full charge detection / re-charge management

3. **Protection detection function**

・Over charge detection / Over discharge detection / Over current detection / Temperature malfunction detection.

4. **Capacity detection function**

・Current accumulation method

5. **Traceability information**

・Battery module manufacture date (currently planning what information to put in)

6. **Communication function**

・Inter-battery module / Inter-BPU102(Protection Unit) communication function

### 2.1.4 Frequency Regulation Application of DESS Tested

Energy storage offers some unique response capability due to the advanced capabilities of the power electronics in the power conversion system, coupled with the fact that energy storage batteries can provide real power on a moments notice. As more renewable generation introduced into the grid and conventional power plants are retired from service the impact of the intermittent and variable nature of the renewable resources make it much more difficult for Independent System Operators of the grid to maintain a constant frequency and minimize Area Control Error (ACE). Energy storage, because of its fast response capability, can provide rapid response frequency regulation capability not possible with other forms of energy resources. Using the Sanyo energy storage system UCSD investigated and demonstrated the feasibility of using energy. Figure 6 below shows an example of the Sanyo DESS output responding to a frequency regulation signal from the Pennsylvania-New Jersey-Maryland (PJM) frequency regulation signal.

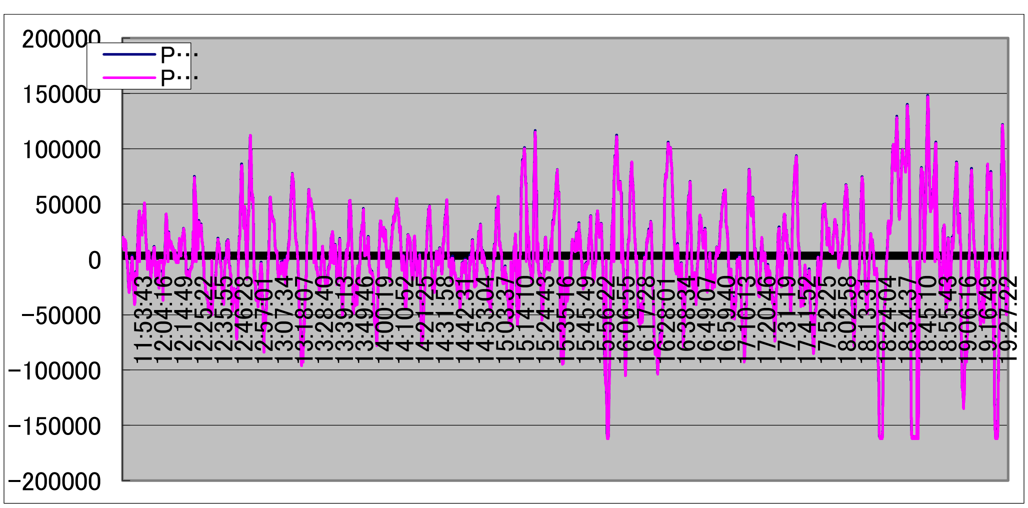


**Figure 6 Sanyo Energy Storage output in response to PJM frequency regulation signal**

## 2.2 125 kW / 65 kWh EV Battery Test Stand DESS

An energy storage system test stand was installed at UCSD in 2012 utilizing 2nd life plug-in electric vehicle (PEV) batteries. This energy storage testing included partners California Center for Sustainable Energy (CCSE), National Renewable Energy Laboratory (NREL), San Diego Gas & Electric (SDG&E), AeroVironment, BMW Group, University of California, Davis. The purpose of this testing is to study the viability of using PEV battery systems in the grid support the DESS market. Among the five primary research tasks and deployment efforts that the project team has completed to date include: (1) assessment of potential second-life applications for used batteries and development of real-world duty-cycles for these battery storage systems, (2) techno-economic analysis of potential markets for repurposed PEV batteries, (3) acquisition of used PEV battery packs and modules of multiple lithium chemistries for initial benchmark and laboratory testing, (4) down-selection and deployment of 68 kWh of used PEV battery packs and modules in long-term field testing within the UC San Diego microgrid.

### 2.2.1 DESS Test Stand Design

UCSD was chosen as the host for the long-term field test site because of its accessibility to many generation and load resources that could be eventually integrated into the control strategies for the batteries. The Battery Test Facility was a $220,000 hardware installation located at Hopkins Parking Structure. It was commissioned in February 2012. Its flexible platform allows for easy replacement of batteries and the ability to switch out one for another. At any one time, the test bed can operate up to four full size EV battery packs (with a 120 kW peak total battery power limit) with independent control channels, and data acquisition. The Battery Control Software (BCS) was specially designed by AeroVironment to provide local and remote control of the batteries. The Battery Control Software communicates with each battery's Battery Management System (BMS) individually via CANbus to command the battery. Remote control of the Battery Control Software can be performed via Modbus. Figure 7 provides a picture of the control software screen that is displayed locally at the test stand.

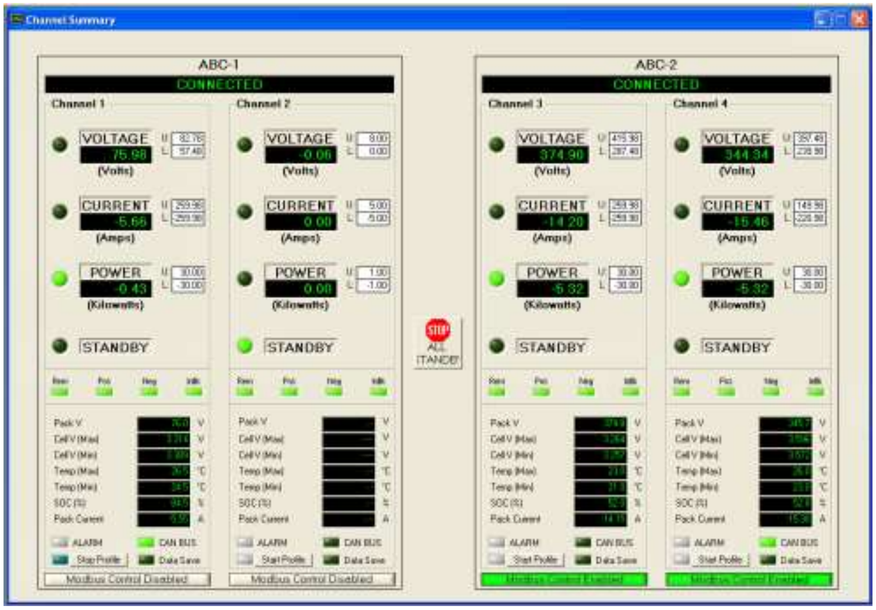


**Figure 7 Control Stand Interface**

### 2.2.2 Test Results

The first year and a half of testing included running week-long predetermined duty cycles on the batteries. Three second-life applications were chosen for cycling because of their feasibility and economic potential. These included back-up power supply, demand charge management, and regulation energy management.

Prior to testing any of the batteries, a set of tests were run to gauge the battery's current state of health and to establish a baseline in which to compare future tests as the battery begins to degrade under second life testing. Eventually, the set of tests were refined and narrowed down to what we now cumulatively call the Reference Performance Test.

The Reference Performance Test includes two parts: capacity measurements and a DC impedance measurement. The capacity measurement portion is broken up into two tests, a C/5 capacity test, and a 1C capacity test. DC impedance is measured through the pulse characterization test. The Reference Performance Test is important because it helps us to study the batteries state of health pre-second life use, and to consistently track the battery's performance and degradation under second-life use.

Figure 8, shows sample data from an October 2013 C/5 Capacity Test performed on one of the batteries.

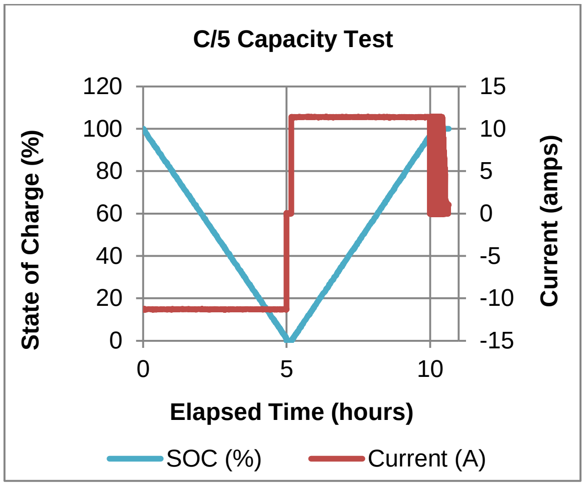


**Figure 8 C/5 Capacity Test Results**

The C/5 capacity test also acts as a proxy for studying our batteries performance under the back-up power application. Because the capacity test calls for a full discharge of the battery from a fully charged state, this cycle mimics what a battery would have to do if it was needed for a back-up power application.

A pulse characterization test was also performed to measure the battery's resiliency and rise time capability. As an example Figure 9 shows the result of running a Pulse Characterization Test on the A123 Pack #2 (Channel 3) on October 7, 2013. Pulses were 10 seconds in length at a 2.5C rate. A charge and discharge pulse was performed at 10% SOC incremented levels, with a single charge at 0% and a single discharge at 100% SOC.

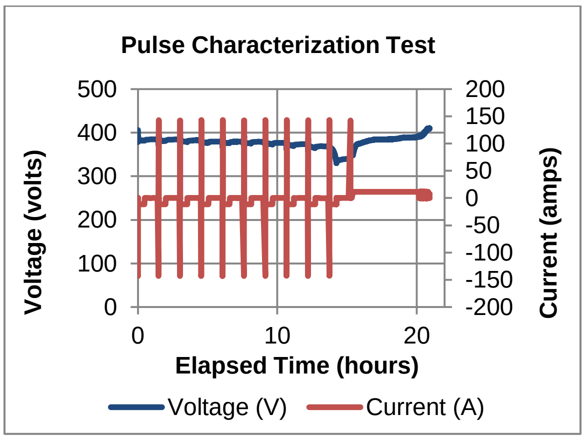


**Figure 9 Pulse Characterization Test**

### 2.2.3 DESS Use Cases tested

Two use case applications have been tested so far to determine battery performance and life expectancy. The two use case applications include Regulation Energy Management (REM) and Demand Charge Management (DCM).

The duty cycle for regulation energy management was developed through collaboration between CCSE, the California Independent System Operator (CAISO) and KnGrid, an ancillary services consulting company to study the viability of battery storage systems participating in the area regulation market. In December 2010, KnGrid, CCSE, and CAISO investigated the possibility of opening up the regulation market to a non-generating resource (NGR), which includes batteries. This required new regulation standards to be set. To study the viability of batteries in the regulation market, CAISO created a cycling model that mimics how generating entities respond to AGC signals which could be tested on batteries. CAISO collected AGC signals from July 1, 2010 to July, 7 2010. The economic viability was studied using these AGC signals combined with 5-minute real-time market (RTM) energy pricing data. The cycling model created from AGC signals was scaled to fit the capacity of a variety of batteries. The profile developed is what we now call a Regulation Energy Management (REM) duty cycle. Figure 10 shows the intended power profile and state of charge performance of a battery pack under REM cycling.

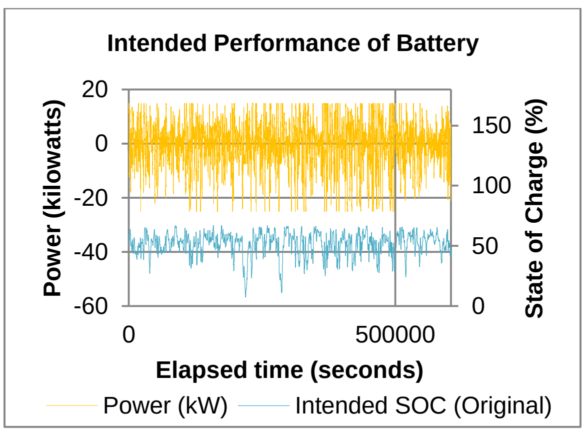


**Figure 10 Intended power profile and state of charge of battery pack under REM duty cycle**

The demand charge management duty cycle has gone through several modifications, starting with development by NREL. UCSD Ph.D. and undergrad students also developed and helped refine a similar demand charge management algorithm which we now consider the short-term DCM duty cycle. The DCM duty cycle was based on historical building load, historical PV generation, and solar and building forecasting. Figure 11 shows the intended power profile and state of charge performance of a battery pack under a short-term DCM duty cycle

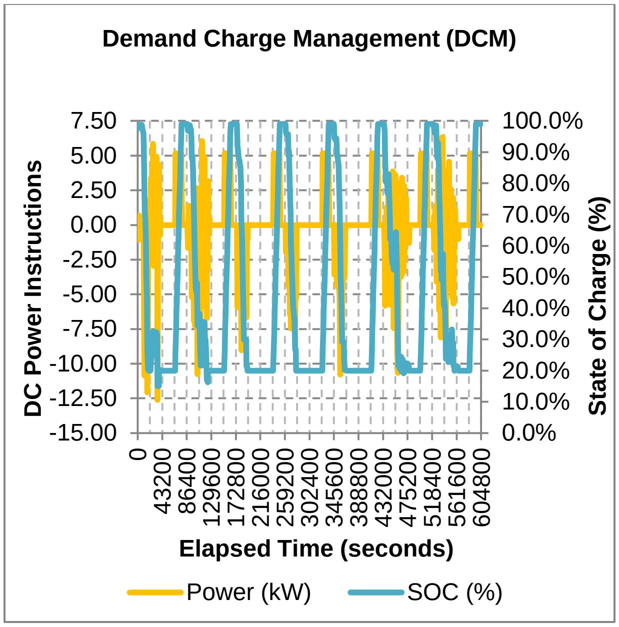


**Figure 11 Intended power profile and state of charge of battery pack under DCM duty cycle**

Long-term DCM field testing is continuing. UCSD has continued to refine the DCM algorithm to control two of our batteries in the test facility. The algorithm lives on OSI Soft's PI Server on the UCSD campus. A solar forecast, building load forecast, and battery dispatch is generated once per day. Each minute, the algorithm reads in real-time building load and PV generation data and makes updates to the battery dispatch. The dispatch is grabbed by Power Analytics' Paladin software and Modbus commands are sent to the Battery Control Software by Paladin. The DCM algorithm tracks the SOC of the battery virtually. To mitigate any issues of the algorithm "battery" and the real batteries' SOC's being out of sync, there is an SOC synchronization and maintenance of the batteries (cell balancing) once per day at 3:00 am. At 3:00 am, the Paladin software overrides control of the batteries and taper charges and balances them to 100%. At 5:00 am, control is handed back to the DCM algorithm which resets its SOC counter to 100%. The DCM algorithm is designed for a 53kW/40kWh system. The batteries in our test facility are around 20 kWh. Therefore, we've operated two of our batteries as one system, cycling each of them at ½ the power command. Additionally, the two batteries running under DCM are of different chemistries which makes this configuration a world's first.

# CHAPTER 3:
# SUMMARY AND CONCLUSIONS

UCSD has conducted long term field testing of Distributed Energy Storage Systems over the last 3 years.  Valuable performance information has been gained but further testing and cycling is required to determine accurate life expectancies.  The DESS tested included both new Lithium-ion batteries and testing used PEV batteries.

DESS can be used for many applications to support the larger power grid, customers, and improve overall system efficiency and reliability.  UCSD tested six different applications for DESS:

- Smoothing of renewable intermittency
- Peak Load Reduction using stored solar PV generation
- Energy Arbitrage
- Frequency Regulation
- Demand Charge Management
- Regulation Energy Management

At the end of 3 years of testing all systems showed little degradation from the initial Reference Performance Test that was done at the beginning of the test period.  Life expectancy will be highly dependent on use the case application used for the DESS.  It is anticipated that life expectancy will be less for applications involving higher depth of discharge (DOD), such as peak load reduction.  Correspondingly life expectancy will longer for DESS applications that involve small DOD, such as frequency regulation or Regulation Energy Management.