Final Long-Term Duty Cycle Report

Demand Charge Management (DCM) Duty Cycle
Battery Packs: A123 #2, Channel 3 and EnerDel, Channel 4

April 2015

PREPARED FOR
National Renewable Energy Laboratory

PREPARED BY
Center for Sustainable Energy

Center for Sustainable Energy

Headquarters
9325 Sky Park Court, Suite 100
San Diego , CA 92123
858.244.1177 *phone*
www.energycenter.org

Office Locations
San Diego
Los Angeles
Oakland

Table of Contents

List of Tables

List of Figures

I. Summary of Operations

This test report provides a summary of the complete long-term demand charge management (DCM) duty cycle testing performed on the A123 Pack #2 for three cycling periods and the EnerDel Pack for one cycling period. Prior to the DCM testing discussed herein, both battery packs were subjected to automotive cycling and over 1.5 years of additional stationary storage cycling. This previous cycling degraded the A123 Pack #2 to a state at which it retained nearly 100% of its nameplate capacity and the EnerDel Pack to a state at which it retained just over 85% of its nameplate capacity. Due to previous cycling, both battery packs displayed approximately 150% of their beginning of life impedance as well. Subsequent long-term DCM testing included over 200 and close to 100 non-consecutive days of DCM cycling on the A123 Pack #2 and EnerDel Pack, respectively, including both prescribed and real-time cycling. Between each approximate 60-day period, there was a Reference Performance Test (RPT) conducted on the battery pack under test. The Reference Performance Tests served as an indication of battery degradation under long-term DCM cycling. Table 1 summarizes the testing time of each DCM cycling period under this long-term protocol.

Table 1: Overview of DCM Cycling Periods

Period	Battery Pack	Time Range	Elapsed Calendar Days[1]	Cycling Days
Period 1	A123	Oct. 2013-May 2014	226.5	85.5
	EnerDel		225.6	99.0
Period 2	A123	May 2014-Nov. 2014	190.1	70.9
Period 3	A123	Nov. 2014-Mar. 2015	119.7	69.0
Total	A123	Oct. 2013- Mar. 2015	536.3	225.4
	EnerDel	Oct. 2013-May 2014	225.6	99.0

---

[1] Elapsed calendar days includes the time for completion of the pre and post Reference Performance Tests.

II. Results of Reference Performance Tests (RPTs)

The Reference Performance Tests consisted of capacity and DC impedance (or resistance) measurements. Summary results of the RPTs conducted before, after, and during long-term DCM duty cycle testing are presented below. All, but two of the tests from the total RPT occurrences during this long-term test protocol, were performed locally via the Battery Control Software (BCS). Table 2 summarizes the results of the capacity tests performed on the A123 Pack #2 and EnerDel Pack during long-term DCM cycling.

Table 2: Summary of Capacity Tests

<table>
<tr><th></th><th colspan="2">Oct. 2013</th><th colspan="2">May 2014</th><th>Nov. 2014</th><th>Mar. 2015</th></tr>
<tr><td></td><td>A123</td><td>EnerDel</td><td>A123</td><td>EnerDel</td><td>A123</td><td>A123</td></tr>
<tr><td>Direct Capacity (Ah)[2]</td><td>56.7</td><td>61.34</td><td>55.6</td><td>59.44</td><td>54.9</td><td>54.2</td></tr>
<tr><td>Direct Capacity as % of Nameplate</td><td>99.5</td><td>85.2</td><td>97.5</td><td>82.6</td><td>96.3</td><td>95.0</td></tr>
<tr><td>Direct Energy (kWh)[3]</td><td>21.2</td><td>20.46</td><td>20.8</td><td>19.80</td><td>20.5</td><td>20.2</td></tr>
<tr><td>Direct Energy Efficiency (%)</td><td>97.6</td><td>98.39</td><td>98.3</td><td>94.28</td><td>97.7</td><td>96.0</td></tr>
<tr><th></th><th colspan="4">Period 1</th><th>Period 2</th><th>Period 3</th></tr>
<tr><td></td><td colspan="2">A123</td><td colspan="2">EnerDel</td><td>A123</td><td>A123</td></tr>
<tr><td>DCM Discharge Throughput (kWh)[4]</td><td colspan="2">1,946,846.0</td><td colspan="2">1,339,590.9</td><td>3,192,056.6</td><td>2,629,211.2</td></tr>
<tr><td>Percent Capacity Change per GWh of DCM Discharge Throughput (%/GWh)[5]</td><td colspan="2">-0.010</td><td colspan="2">-0.020</td><td>-0.004</td><td>-0.005</td></tr>
</table>

---

[2] The Direct Capacity (Ah) is the direct discharge capacity measured during the C/5 capacity test.

[3] The Direct Energy (kWh) is the direct discharge energy measured during the C/5 capacity test.

[4] The DCM Discharge Throughput (kWh) is the absolute value of the kWh Out during DCM cycling days.

[5] The Percent Capacity Change per GWh DCM Discharge Throughput (%/GWh) is the ratio of capacity loss as a percentage of nameplate capacity (57 Ah) to the GWh of energy discharged out of the battery during DCM cycling. It is important to note that each cycling period did not have the same amount of GWh discharge throughput.

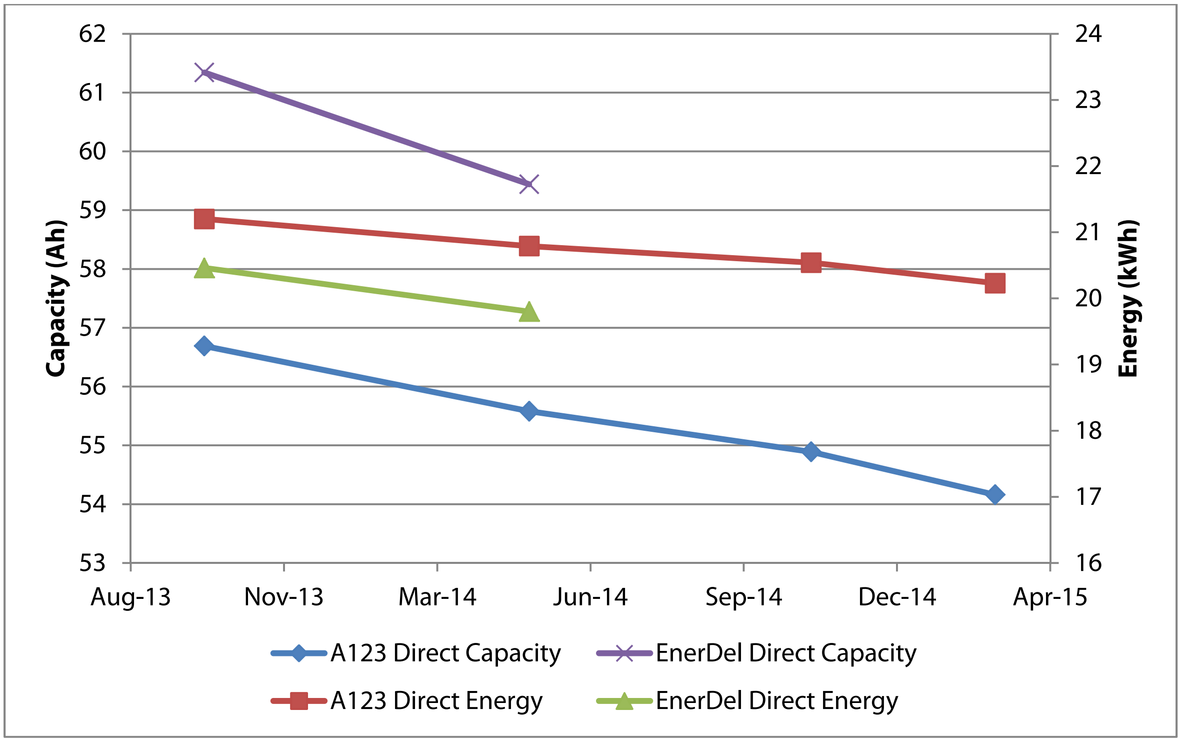

Figure 1: Capacity Degradation of Battery over DCM Cycling

Before each capacity test, the testing protocol called for the battery cells to be fully charged and balanced to 100% SOC. The A123 Pack #2 is considered fully charged and balanced when the minimum cell voltage is at least 3.59 V and the maximum cell voltage is at least 3.6 V. Moreover, the EnerDel Pack is considered fully charged and balanced when the minimum cell voltage is at least 4.08 V and the maximum cell voltage is at least 4.1 V. This protocol of charging and balancing to 100% SOC was achieved before all capacity tests conducted in this report.

The A123 Pack #2 RPTs in October 2013 and May 2014 show that 2.0% of nameplate capacity was lost over this period. From May 2014 to November 2014 an additional 1.2% of nameplate capacity was lost and from November 2014 to March 2015 an additional 1.3% of nameplate capacity was lost due to DCM cycling. For the EnerDel Pack, 2.6% of nameplate capacity was lost due to DCM cycling between October 2013 and May 2014

Table 3 and Figure 2 below summarize the average DC impedance of the A123 Pack #2 and EnerDel Pack cells for the charge and discharge pulses of each Pulse Characterization Test (PCT). While conducting each PCT, we did not control for cell temperatures. This control capability was not available at the employed test facility. In general, though, increased cell temperatures will result in decreased resistance and decreased cell temperatures will result in increased resistance. Between May 2014 and March 2015, we see this trend of increasing resistance with decreasing average cell temperature for the A123 Pack #2. Between October 2013 and May 2014, we also see this trend with the EnerDel Pack. However, in Table 3, as the cell temperature decreases, the resistance also decreases between October 2013 and May 2014 for the A123 Pack #2. Although, the impedance trend between October 2013 and May 2014 is unexpected, it is difficult to accurately compare impedance without controlling for cell temperature. Therefore, had we wanted to more accurately compare DC impedance degradation over time for both battery packs during DCM cycling, we would have needed to control for cell temperatures when performing each PCT.

Comparison of the October 2013 and May 2014 test data for the A123 Pack #2, where the cell temperatures were similar, however, implies that the resistance of this battery pack has not been significantly impacted by DCM cycling, at least for a single cycling period. As for the EnerDel Pack, there is not a clear picture on whether the resistance has been impacted by DCM cycling due to variability in average cell temperatures between each PCT.

Table 3: Average DC Impedance and Average Temperatures of Battery Pack Cells during DCM Cycling

Pulses	Oct. 2013		May 2014		Nov. 2014	Mar. 2015
	A123	EnerDel	A123	EnerDel	A123	A123
Charge (mΩ)	101.6	119.6	100.9	118.8	105.2	113.7
Discharge (mΩ)	93.8	113.7	93.1	113.0	100.0	108.4
Temperature (°C)	27.2	27.1	26.7	29.0	25.7	23.2

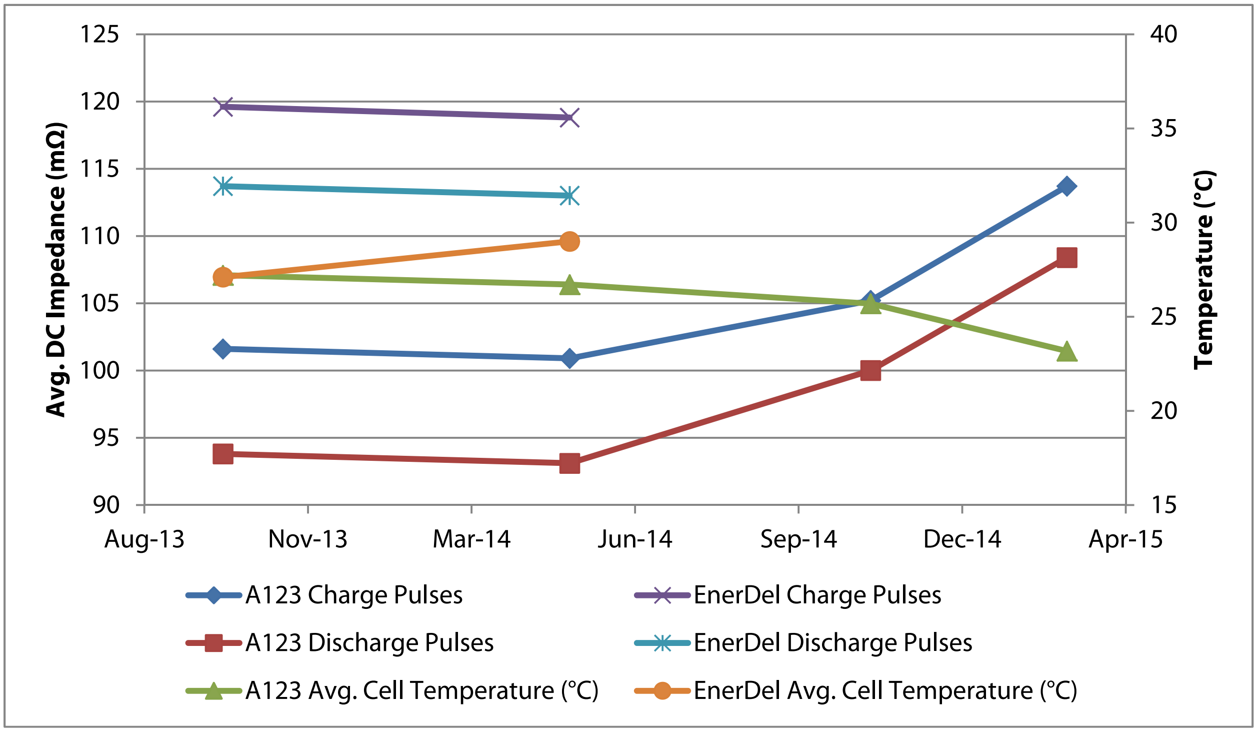

Figure 2: Average DC Impedance and Average Temperatures of Battery Pack Cells during DCM Cycling

III. DCM Cycling

In this long-term testing period, the A123 Pack #2 and EnerDel Pack were cycled under both a prescribed DCM duty cycle and a real-time DCM algorithm. The prescribed DCM duty cycle was a 7-day duty cycle (168 hours) run locally through the Battery Control Software (BCS), while the real-time DCM algorithm was run utilizing a web-integrated software platform, Paladin, from Power Analytics Corporation. The real-time DCM algorithm incorporated real-time campus resources, including solar PV output and a building load. In addition, a forecasted solar PV output was generated using North American Mesoscale Forecast System (NAM) global horizontal irradiance (GHI) data from the National Centers for Environmental Prediction (NCEP) and a forecasted building load was generated using historical building load data.

During long-term DCM cycling, the A123 Pack #2 was cycled under the prescribed DCM duty cycle for a total of 103.5 days and under the real-time DCM algorithm for a total of 121.9 days, resulting in a total of 225.4 days of DCM cycling overall. During the course of long-term DCM cycling, the prescribed DCM duty cycle was attempted a total of 27 times on the A123 Pack #2. Of those 27 attempts, there were only 7 times in which the battery pack completed the full seven-day cycle (168 hours). Often times, the duty cycle would be stopped early due to the ABCs going offline or in order to utilize the battery pack for other testing purposes, including but not limited to, testing python scripts via Paladin and restarting the BCS.

During period 1 of long-term DCM cycling, the EnerDel Pack was cycled under the prescribed DCM duty cycle for a total of 71.6 days and under the real-time DCM algorithm for a total of 27.4 days, resulting in a total of 99.0 days of DCM cycling overall. During the course of long-term DCM cycling, the prescribed DCM duty cycle was attempted a total of 17 times on the EnerDel Pack. Of those 17 attempts, there were only 3 times in which the battery pack completed the full seven-day cycle (168 hours). Often times, the duty cycle would be stopped early for various reasons, including but not limited to, switching over to running the real-time DCM algorithm and restarting the BCS.

a. Prescribed DCM

Figure 3 below showcases a sample week (November 25-Decebmer 2, 2014) during DCM cycling period 3 during which the prescribed duty cycle was run on the A123 Pack #2. In the figure, we can see that the cell voltages stayed within the minimum and maximum cell voltage limits – 2.5 V and 3.6 V, respectively. During other cycling days throughout periods 1 and 2[6], though, the maximum cell voltage of the A123 Pack #2 hit the maximum cell voltage limit. This was not a concern as long as it occured at the end of the day during battery re-charge, avoiding interference with demand reduction. The A123 Pack #2 was cycled between about 20% and 100% state of charge (SOC). All the prescribed DCM duty cycles run on the A123 Pack #2 were similar to the one shown in Figure 3.

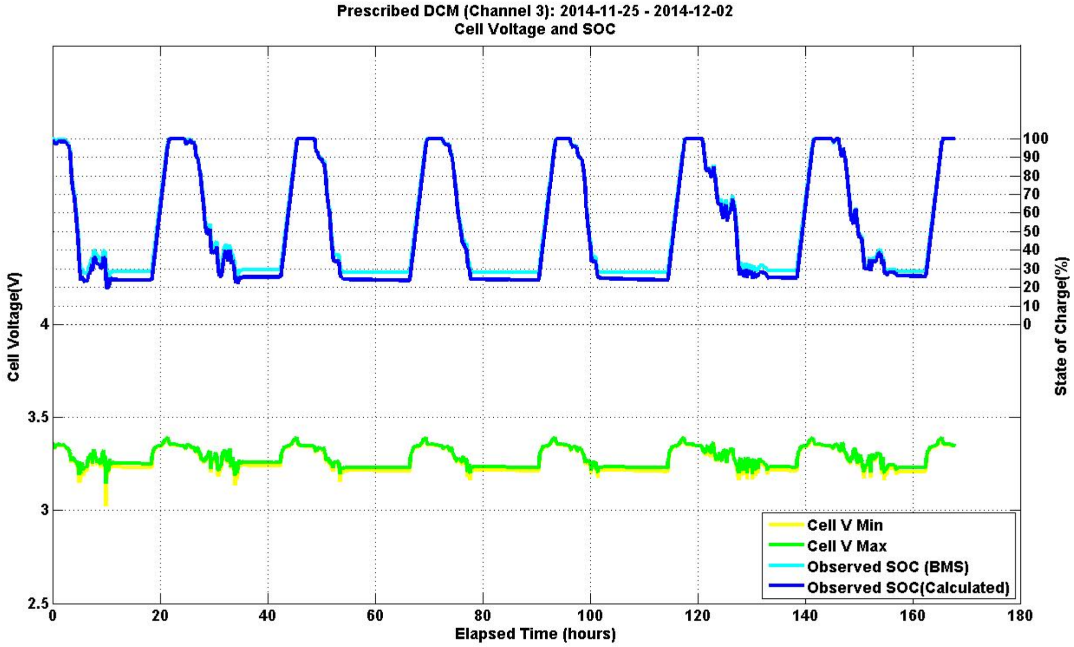

Figure 3: Cell Voltage and SOC Trends for Complete 7-day DCM Duty Cycle on the A123 Pack #2 (11-25-2014 to 12-02-2014)

Figure 4 below showcases a sample week (February 21-28, 2014) during DCM cycling period 1 during which the prescribed duty cycle was run on the EnerDel Pack. In the figure, we can see that the minimum cell voltage stayed within the minimum cell voltage limit – 2.5 V, while the maximum cell voltage exceeded the maximum cell voltage limit – 4.1 V. However, by looking at the figure, we can see that the times at which the battery hit its maximum cell voltage limit were at the end of the day when it was appropriate that the battery was fully re-charged in

---

[6] During period 3, the A123 Pack #2 was frequently not charged and balanced before initiating the prescribed DCM duty cycle, whereas the other testing periods, the battery pack was mostly charged and balanced beforehand.

preparation for the next day of cycling. Additionally, because the minimum and maximum cell voltages were considerably close during these end-of-day periods, it is likely that the cells of the EnerDel Pack were balanced at the end of each day. This is ideal because cycling batteries over an extended period can cause imbalance in cells which can lead to reduced available capacity. Lastly, the EnerDel Pack was cycled between about 20% and 100% state of charge (SOC). All the prescribed DCM duty cycles run on the EnerDel Pack were similar to the one shown in Figure 4.

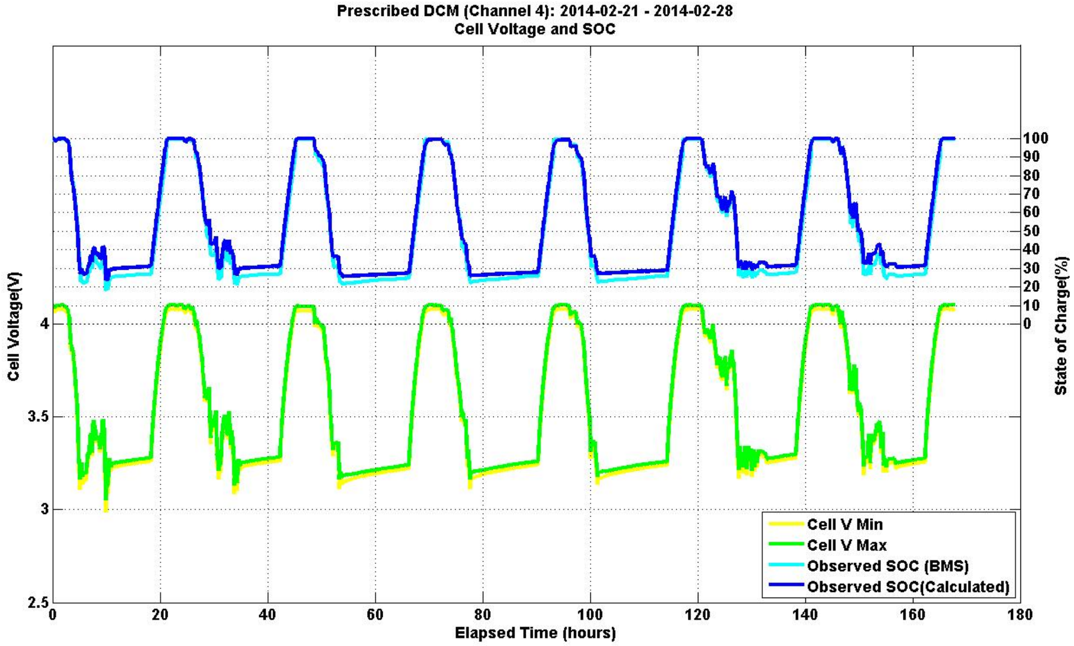

Figure 4: Cell Voltage and SOC Trends for Complete 7-day DCM Duty Cycle on the EnerDel Pack (02-21-2014 to 02-28-2014)

b. Real-time DCM

Figure 5 below highlights a day during DCM cycling period 1, January 9, 2014, when the DCM algorithm was cycled on the EnerDel Pack. In the figure, Plot 3 shows the battery discharging as intended, keeping the net load of building load minus solar PV output below the net load target by as much as possible. Battery discharge was able to reduce the daily peak load by almost 20 kW. The battery was cycled between 60% and 100% SOC. During this day the solar PV output was over predicted slightly, while the building load was fairly accurately predicted.

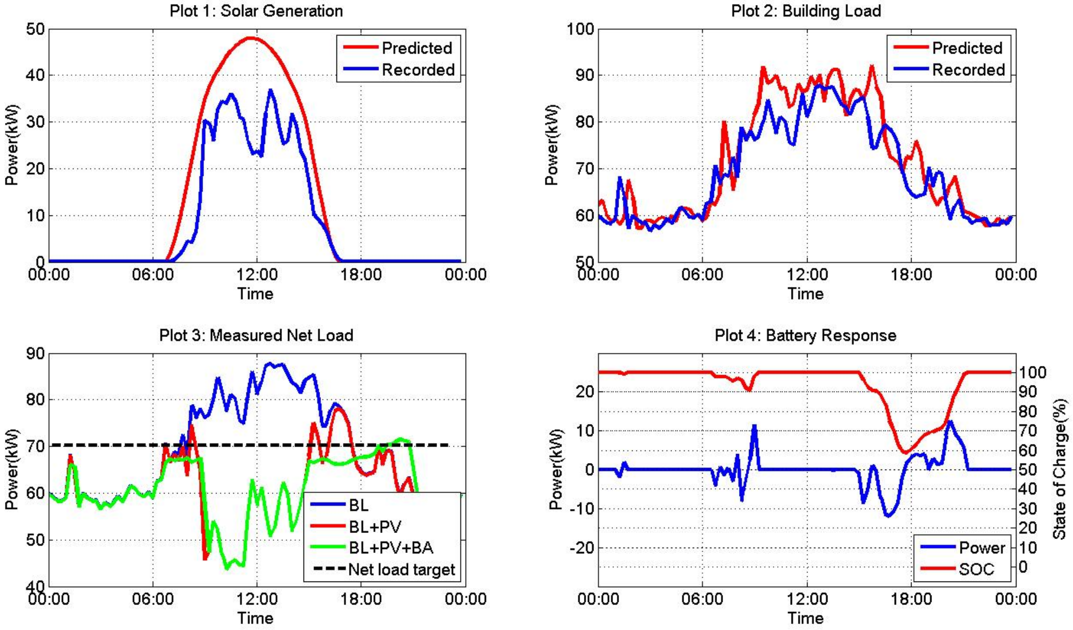

Figure 5: Real-time DCM Results from 01-09-2014

c. One-way Energy Efficiency

Table 4 below summarizes the effective one-way energy efficiency of a representative complete prescribed DCM 7-day duty cycle run from each of the DCM cycling periods. The effective one-way energy efficiency of the A123 Pack #2 remains relatively constant between about 96%-98% throughout long-term DCM cycling, which agrees well with the RPT data that suggests battery pack resistance is largely constant over the test period. The single, effective one-way energy efficiency of the EnerDel Pack for period 1 is not sufficient enough to determine resistance degradation of the battery pack over the entire long-term DCM cycling period. See below for the methodology used to calculate the effective one-way energy efficiency of each battery pack.

Table 4: Effective One-way Energy Efficiency of Battery Packs during each DCM Cycling Period

	Period 1		Period 2	Period 3
	A123	EnerDel	A123	A123
Energy Efficiency (%)	97.29	97.48	96.88	97.75

Effective One-way Energy Efficiency (*eff*) Calculation Methodology:

$$E_{end} = E_{start} + [E_{in} * eff] - \left[\frac{E_{out}}{eff}\right]$$

$$E_{end} = \left[SOC(Ah)_{ending}\right] * \left[\frac{C}{5} measured\ discharge\ energy\right]$$

$$E_{start} = \left[SOC(Ah)_{starting}\right] * \left[\frac{C}{5} measured\ discharge\ energy\right]$$

Where

- E_{end} = Stored energy in the battery at the end of the test
- E_{start} = Stored energy in the battery at the beginning of the test
- E_{in} = Integral of DC charge power over the test
- E_{out} = Integral of DC discharge power over the test
- eff = Effective one-way energy efficiency

IV. Conclusions

We have learned about the performance of Lithium-ion battery packs, in particular the A123 Pack #2 and EnerDel Pack, under long-term demand charge management (DCM) duty cycle testing. Performance of the battery packs was measured by studying the batteries' ability to follow the prescribed duty cycle as requested by the intended DCM power profile and the real-time DCM algorithm and via direct measurement of capacity, energy, and resistance using a Reference Performance Test (RPT).

The primary finding of this study is the minimal impact of DCM cycling on the degradation of a Lithium Iron Phosphate battery pack (i.e. A123 Pack #2). Between the beginning and end of long-term DCM cycling (over 200 days), the A123 Pack #2 degraded by only 4.5% of nameplate capacity – from 56.7 Ah to 54.2 Ah. There is not enough data on the EnerDel Pack for comparison purposes with the A123 Pack #2 on degradation rates, but between the beginning and end of period 1 of long-term DCM cycling (almost 100 days); the EnerDel Pack degraded 2.6% of nameplate capacity – from 61.34 Ah and 59.44 Ah.

However, during period 1, the degradation rate in capacity is two times greater for the EnerDel Pack than for the A123 Pack #2. The degradation rate of the A123 Pack #2 is 0.010% capacity loss per GWh of DCM discharge throughput while the degradation rate of the EnerDel Pack is 0.020% capacity loss per GWh of DCM discharge throughput. In period 1 of DCM cycling, the A123 Pack #2 degraded by 2.0% of nameplate capacity, but consideration of calendar time and throughput both play roles in contributing to degradation. In period 1, the A123 Pack #2 is cycled more (i.e. throughput) than the EnerDel Pack, but the EnerDel Pack is cycled for a longer period (i.e. calendar time) than the A123 Pack #2.

The A123 Pack #2's degradation rate as capacity loss per GWh of DCM discharge throughput was nearly cut in half from 0.010% in period 1 to 0.004%-0.005% in periods 2 and 3, respectively. This might be indicative of the battery pack's degradation trend with degradation rates tapering initially until an abrupt drop in capacity at which point the battery would be removed from second-use and recycled.

The change in DC impedance of the A123 Pack #2's cells is difficult to quantify because cell temperature was not controlled for during the pulse characterization tests; however, the impedance measurements we have suggest insignificant change in DC impedance over the course of testing. Calculation of effective one-way energy efficiency under DCM cycling supports this conclusion, as it varies by less than 1% over the duration of testing.

Lastly, a secondary finding of this study is the benefit of individual DC-DC converters for each battery pack. With our power electronics, communications, and control setup at the test facility, we were able to run the two battery packs of differing chemistries and cycling limits as a single energy storage resource under the DCM real-time algorithm. During period 1, when both battery packs were utilized for testing, we were able to disconnect one pack from control of the DCM algorithm without affecting operation of the other. However, individual DC-DC converters add extra costs and may not be feasible in long–run commercialization of second-use batteries. Moreover, this leads to the need for standardization across battery packs, so that integration into larger second-use energy storage systems is easier.

Collectively, these results suggest that such Lithium-ion batteries could sufficiently handle the technical requirements of demand charge management applications for at least one year following service in an automotive application. Furthermore, the low rate of capacity loss and negligible resistance growth could be linearly extrapolated to suggest an impressively long second-use DCM service life. However, Lithium-ion battery degradation is known to be nonlinear; thus, additional testing is necessary to confidently assess the total DCM service life.