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Energy Storage for DC Fast Chargers Development and Demonstration of Operating Protocols for 20-kWh and 200-kWh Field Sites

Russell Newnham[a]
Sally (Xiaolei) Sun[a]
Donald Karner[a]
James Francfort[b]

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[a] ECOtality North America
[b] Idaho National Laboratory

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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ABSTRACT

Many of the currently available and future electric vehicles can be fast charged, and, typically, at least 50% of the battery capacity can be returned in 15 to 20 minutes. This charge rate requires a power of at least 50 kilowatts, which can be expensive in terms of both infrastructure and electric utility demand charges. One potential way of minimizing this cost is to charge the electric vehicle with combined battery and grid power, thereby reducing the peak load on the grid. Many sizes and configurations are possible for such a battery. This study examines two possibilities: (1) a 20-kilowatt hour (kWh) battery energy storage (BES) system and (2) a 200-kWh BES system, as well as developing standard test procedures for assessing the suitability of battery technologies for use in such systems.

A simple characterization test on the battery candidates for the BES system was developed. Three lithium-based battery technologies (i.e., Sony/US26650FT, Panasonic/NCR18650, and A123/ANR26650MIA) were subjected to the test. The results suggested that the Sony/US26650FT and A123/ANR26650MIA battery technologies should outperform the Panasonic/NCR18650 battery technology for this application.

Two simulated laboratory profiles for assessing the longer-term performance of batteries operated under the BES system were developed and validated. The first simulated BES profile was based on a battery capacity of 20 kWh, while the second assumed a capacity of 200 kWh. A series of performance metrics were developed to assist with performance comparisons among the battery types undergoing the two profiles.

The three battery types were operated under the simulated 20-kWh BES profile for 3 months. The results obtained during this test period were consistent with those suggested by the screening test. The Sony/US26650FT and A123/ANR26650MIA battery technologies outperformed the Panasonic/NCR18650 battery technology. The Panasonic/NCR18650 battery technology failed after just 19 days, whereas the Sony/US26650FT and the A123/ANR26650MIA battery technologies were still delivering 88% and 86% of their initial capacities, respectively, at the end of the 3-month test.

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TABLES

ACRONYMS

Ah	ampere-hour
BES	battery energy storage
DC	direct current
DCFC	direct current fast charger
EODV	end-of-discharge voltage
EV	electric vehicle
kW	kilowatt
kWh	kilowatt hour
SOC	state of charge
TOCV	time-of-charge voltage
Wh	watt hour

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1. INTRODUCTION

Fast chargers for on-road electric vehicles (EVs), commonly defined as 50-kW or higher in-charge power and referred to as direct current (DC) Level 2 electric vehicle supply equipment units or DC fast charge (DCFC) units, are already in use. DCFC units will place a large power demand on the local electric grid. DCFC units that range from 40 to 120 kW are currently commercially available. The power demanded from DCFC units requires an expensive installation, typically requiring the electric utility to install a new metered service. Additionally, at this power level, most electric utilities implement demand charges that range from $10 to $15 per kW for each billing period. This could result in a monthly demand charge up to $1,200 per month for a 60 kW DCFC unit. Assuming the DCFC unit completes five charges per day, the EV owners utilizing this DCFC unit will pay $4 to $6 per charge just to cover demand charges. This puts DCFC at a significant economic disadvantage, because a full recharge, using a less expensive alternating current Level 2 electric vehicle supply equipment unit at home, overnight, has no demand charges.

To reduce the demand that a DCFC unit places on the electric grid, local energy storage can be utilized to supply some, if not all, of the power and energy required for fast charging. This energy storage can be charged between supporting fast charge events at a slow rate in order to minimize power demand. This charging can occur immediately after discharge to ready the energy storage device for the next discharge (i.e., vehicle fast charge), it can occur at night (when demand on the grid is low), or during periods of high renewable energy availability, allowing a reduction in energy cost for charging and the increased absorption of renewables.

Battery energy storage (BES) systems present a viable means to implement DCFC unit demand reductions. Because the battery is stationary, neither gravimetric nor volumetric energy density is an issue. Further, vibration resistance and crash integrity are not important. However, the battery must be inexpensive and long-lived in order to effectively offset electric utility demand charges.

As a result of these benefits, DCFC units for on-road EVs that utilize energy storage will likely soon appear. However, no procedural methods currently exist to evaluate the performance of energy storage devices associated with on-road EV fast chargers. Therefore, two battery test cycles were developed for testing batteries in the laboratory, simulating likely daily use in the field. Idle time (when the battery is not operating during the cycle) was eliminated to accelerate the actual time needed to perform life-cycle testing on the battery. The test cycles were derived based on maximum power and energy values that a complete battery pack would require to support fast charging. The profiles were then verified, with the most promising used for a 3-month test, on three different battery technologies (note: these battery types were first subjected to a simple characterization procedure that was designed to identify unsuitable technologies). This testing yielded information on how each evaluated battery technology reacted to the proposed test cycle and on the ability of the test cycle to quantify battery performance in the BES system.

2. OBJECTIVES

The objectives of the program of work are as follows:

- Develop laboratory test procedures for evaluating the performance of a DCFC BES system.
- Validate the test procedures using different lithium battery technologies and obtain preliminary information on how effective DCFC units are at mitigating the electric utility demand charges for DC fast charging.

3. WORK PROGRAM

The tasks of the work program are described in Table 1.

Table 1. Work program.

Task	Requirement
Task 3.14.1	Develop characterization procedure for the battery candidates and validate
Task 3.14.2	Select and validate three lithium battery technologies
Task 3.14.3	Develop a longer-term test procedure for the 20-kWh BES system
Task 3.14.4	Develop performance metrics for battery evaluation under the 20-kWh BES profile
Task 3.14.5	Cycle three lithium battery technologies under the 20-kWh BES profile for 3 months
Task 3.14.6	Develop a longer-term test procedure for the 200-kWh BES system

4. RESULTS

4.1 Task 3.14.1: Characterization Procedure for the Battery Energy Storage System Battery Candidates

Life testing of batteries is a time-consuming and expensive process. Therefore, a simple characterization procedure that helps predict the battery's performance when used to fast charge EVs (in conjunction with the grid) was developed. The method is predictive in nature, does not involve life cycling of batteries and can provide useful information in a matter of days.

The characterization procedure for the BES system battery candidates is detailed as follows (refer to Appendix for battery test specifications):

(a) Selected and assembled a string or individual cells; the cells were open to the atmosphere with no insulating effect from packaging.

(b) Measured internal resistance over the entire range of state of charge (SOC).

(c) Measured discharge performance at various rates (e.g., 0.5C, 1C, 1.5C, and 2C) using a 1C charge rate, while monitoring cell temperature (ambient temperature was maintained at 25°C).

4.2 Task 3.14.2: Battery Selection and Validation

4.2.1 Battery Selection

Three lithium battery technologies were selected for the procedure validation study. Their specifications are summarized in Table 2. It can be seen that the capacity of the cells was between 2.3 and 2.85 ampere-hour (Ah) and the nominal voltages varied between 3.2 and 3.6 volts.

Table 2. Specifications of lithium batteries.

	Sony	A123	Panasonic
Chemistry	$LiFePO_4$	$LiFePO_4$	Li Ni/Al/Co
Model	US26650FT	ANR26650M1A	NCR18650
Nominal voltage	3.2	3.3	3.6
Rated capacity (Ah)	2.85	2.3	2.75
Top-of-charge voltage	3.6	3.6	4.2
Charging cutoff current (A)	0.1	0.1	0.55
End-of-Discharge voltage	2.0	2.0	2.5

4.2.2 Internal Resistance at Various States of Charge

The internal resistance of the three battery technologies was measured at a range of SOCs and the results are summarized in Figure 1. The internal resistances of both the Sony/US26650FT and the A123/ANR26650MIA batteries are similar, whereas that of the Panasonic/NCR18650 unit is much higher. This result suggested that the Panasonic/NCR18650 unit may be more susceptible to heating than the other battery types at high rates of discharge.

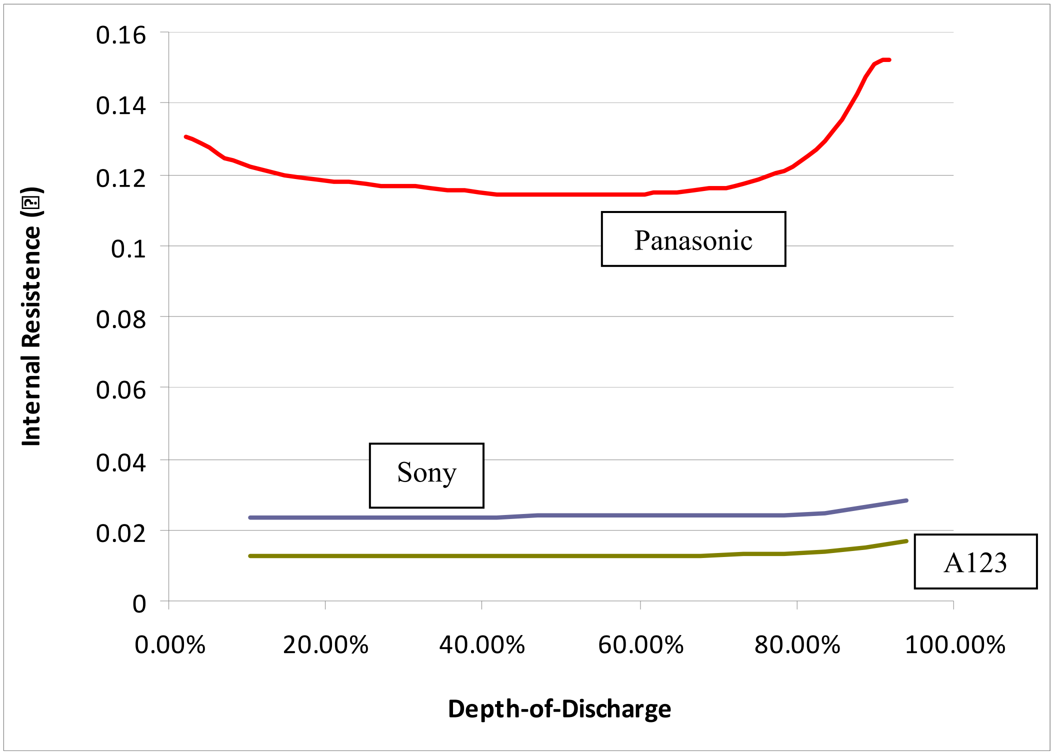

Figure 1. Internal resistance of lithium batteries at states of charge.

4.2.3 Discharge Performance at Different Rates of Discharge

The discharge performance of the three battery technologies is shown in Figures 2 through 7 and Table 3 (note: the discharge rate varied from 0.5 to 2C, but all charging was conducted at 1C).

The capacity (measured in Ah) of the three battery technologies did not change as the discharge rate increased (Table 3). However, the energy (measured in Wh) available from the Panasonic/NCR18650 battery technology dropped significantly at higher rates relative to that of the other battery technologies. This behavior is consistent with the recorded discharge voltage, where the Panasonic/NCR18650 battery technology dropped faster than the other variants (Figures 5 through 7). Further, the operating temperature of the Panasonic/NCR18650 battery technology was considerably higher than that of the others (Figures 2 through 4). These results are supported by the internal resistance measurements, which suggest that the Panasonic/NCR18650 battery technology is more susceptible to heating than the other two types (Figure 1).

In summary, the relatively higher operating temperatures, voltage drop, and internal resistance of the Panasonic/NCR18650 battery technology suggested that it was not as well suited to a high-rate BES system compared to the Sony/US26650FT and A123/ANR26650MIA battery technologies.

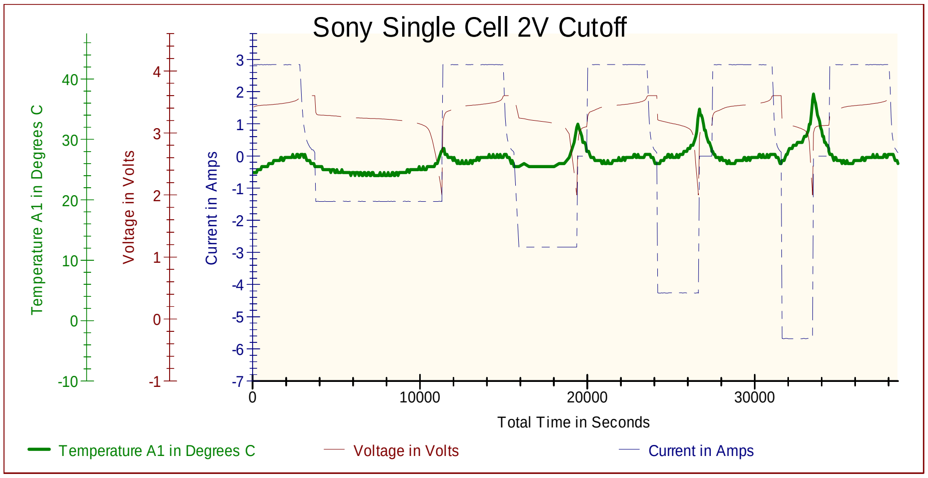

Figure 2. Sony/US26650FT cell - voltage and temperature during discharge (0.5C, 1C, 1.5C, and 2C discharge; 1C charge).

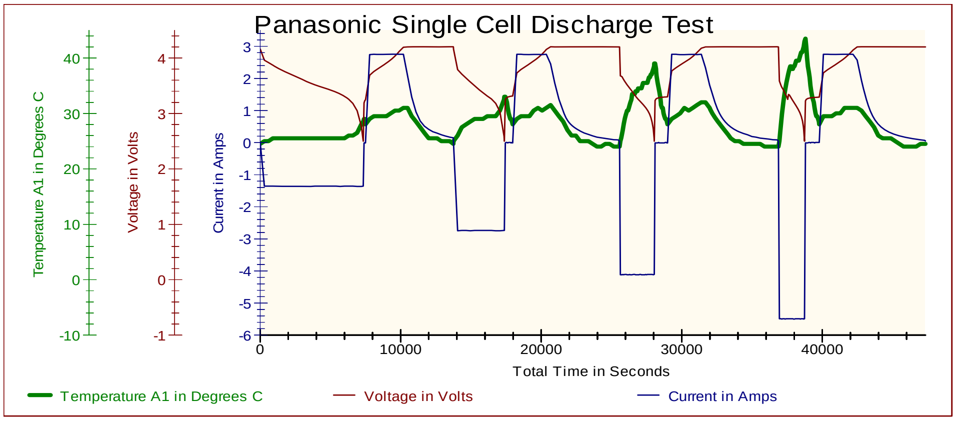

Figure 3. Panasonic/NCR18650 cell - voltage and temperature during discharge (0.5C, 1C, 1.5C, and 2C discharge; 1C charge).

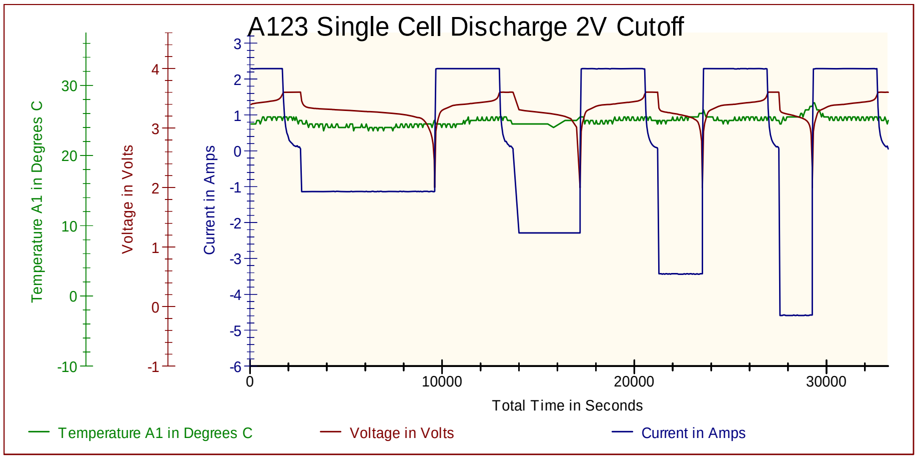

Figure 4. A123/ANR26650M1A cell - voltage and temperature during discharge (0.5C, 1C, 1.5C, and 2C discharge; 1C charge).

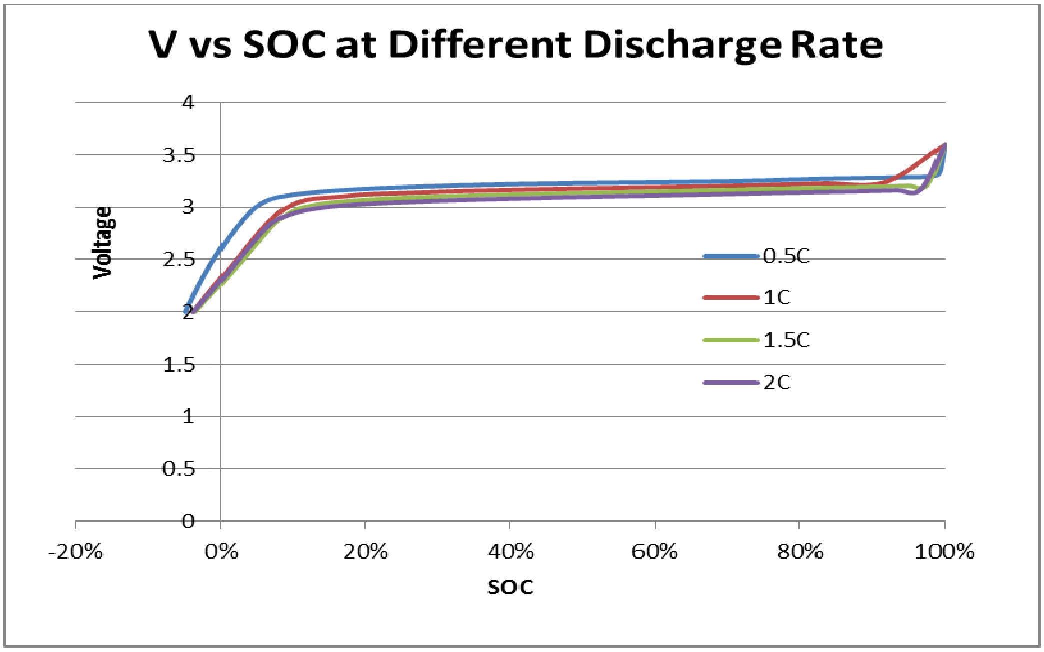

Figure 5. Discharge voltage of Sony/US26650FT battery at different rates.

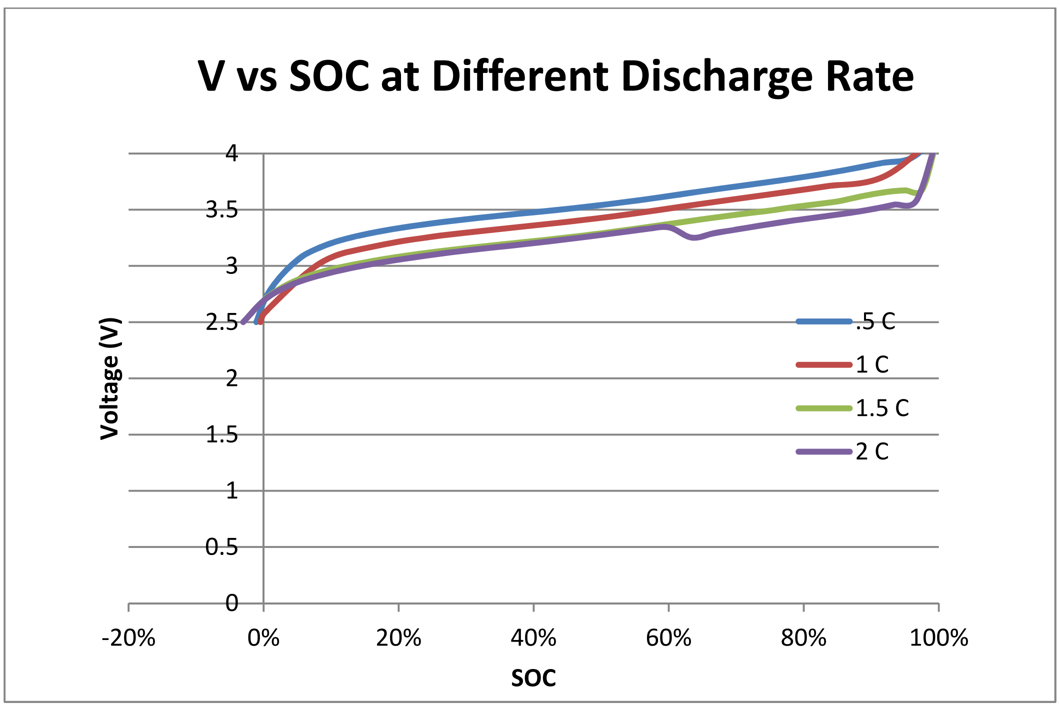

Figure 6. Discharge voltage of Panasonic/NCR18650 battery at different rates.

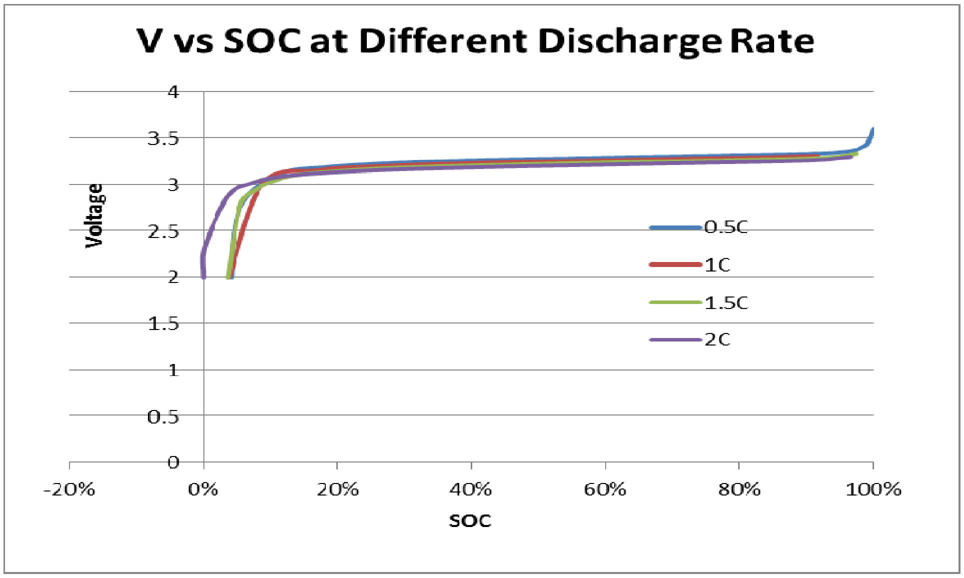

Figure 7. Discharge voltage of A123/ANR26650M1A battery at different rates.

Table 3. Performance of lithium batteries.

	Sony	Panasonic	A123
Discharge Rate	Measured Discharge Capacity (Ah)		
0.5C discharge rate	-3.0	-2.8	-2.2
1C discharge rate	-3.0	-2.8	-2.2
1.5C discharge rate	-3.0	-2.8	-2.2
2C discharge rate	-3.0	-2.8	-2.2
	Measured 1C Charge Return (Ah)		
1C charge rate	3.0	2.8	2.2
	Measured Discharge Energy (Wh)		
0.5C discharge rate	-9.2	-9.7	-7.0
1C discharge rate	-9.1	-9.4	-7.0
1.5C discharge rate	-9.0	-9.2	-7.0
2C discharge rate	-8.9	-9.1	-7.0
	Measured Charge Energy (Wh)		
1C charge rate	10.1	11.1	7.4
Energy density (Wh/kg)	107.5	205.7	100.7
Cell efficiency	90%	84%	95%

4.3 Task 3.14.3: Test Profile for Evaluating Battery Performance in a 20-kWh Battery Energy Storage System

A BES system employed to assist the electric grid to recharge EVs will experience a wide range of operating conditions, including the number of vehicles to be charged per day and the level of recharge required for each vehicle. At one end of the scale, there may be only a few EVs requiring a minor daily recharge (i.e., 30% of battery capacity), with recharges spread out evenly throughout the day. At the other extreme, many EVs may require a moderate daily recharge (i.e., 60% of battery capacity) during peak travel times, requiring large energy charges with short periods between charges. Obviously, this latter example would reduce the lifetime of the BES system compared to that of the lighter duty. The profile developed in this study was designed to fall somewhere between these two scenarios, which represents a realistic scenario for a medium-use BES system supporting an EV fast charge station. It also was based on ECOtality's experience with partial-SOC operation.

The procedure developed, termed the 20-kWh BES profile, assumes that the BES system has a capacity of 20 kWh and that the EV battery being charged has a capacity of 24 kWh. It also assumes that the electric grid could contribute a continuous 20 kW with the BES system supplementing up to 30 kW. When a battery is charged, the charge power is not constant throughout the charge and begins to drop off in an approximately linear fashion near the end of the charge (Figure 8). In this case, the battery contribution decreased when the charge power decreased, while the grid contribution initially remained unchanged, eventually the grid contribution decreased along with the total charge power.

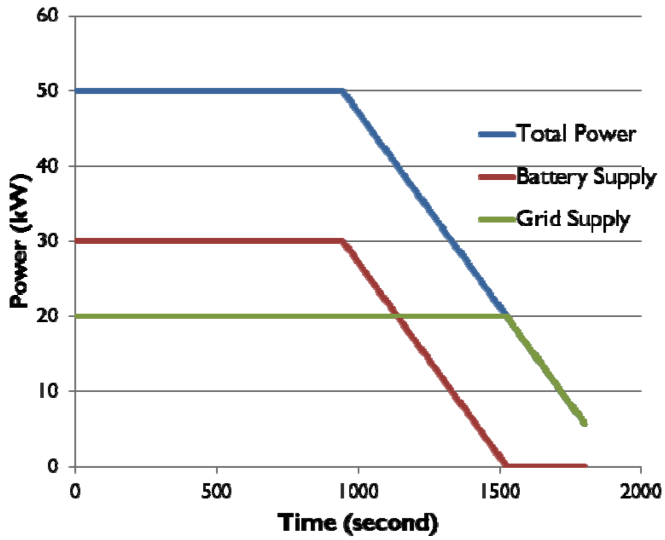

Figure 8. Power profile for total power, battery, and grid contributions.

Therefore, a 50-kW total is available during recharge, which corresponds to a maximum discharge rate for the BES system at 1.5C. It is important to note that the vehicle recharging algorithm is controlled by the vehicle's battery management system and not by the electric vehicle supply equipment unit. In this example, charging enters the voltage control regime at a SOC of around 60%. However, this power tapering point varies depending on the vehicle type, ambient temperature, and vehicle conditions.

The 20-kWh BES profile is shown schematically in Figure 9. The SOC of the BES system at the commencement of charging is shown in red (rectangle box) and the corresponding SOC range of the vehicle battery being charged is shown in black (oval box) (note: rests between charging and discharging are minimized to allow a complete 24-hour day to be compressed into approximately 6 hours).

The two charging scenarios are shown in Table 4. As displayed in Figure 9, the BES system started the day at 100% SOC. It then charged a vehicle battery from 30 to 90% SOC (required approximately 5.9 kWh from the BES system and took 24.6 minutes). In the process, the BES system was discharged at a 1.5C rate from 100 to 70% SOC. The second vehicle then came in and its battery was charged from 30 to 60% SOC (required approximately 4.3 kWh and took 8.6 minutes), during which time the BES system battery was discharged from 70 to 48%. The BES system battery was then recharged from 48 to 70% from the main grid at a 1C rate and was then ready to charge the next vehicle battery.

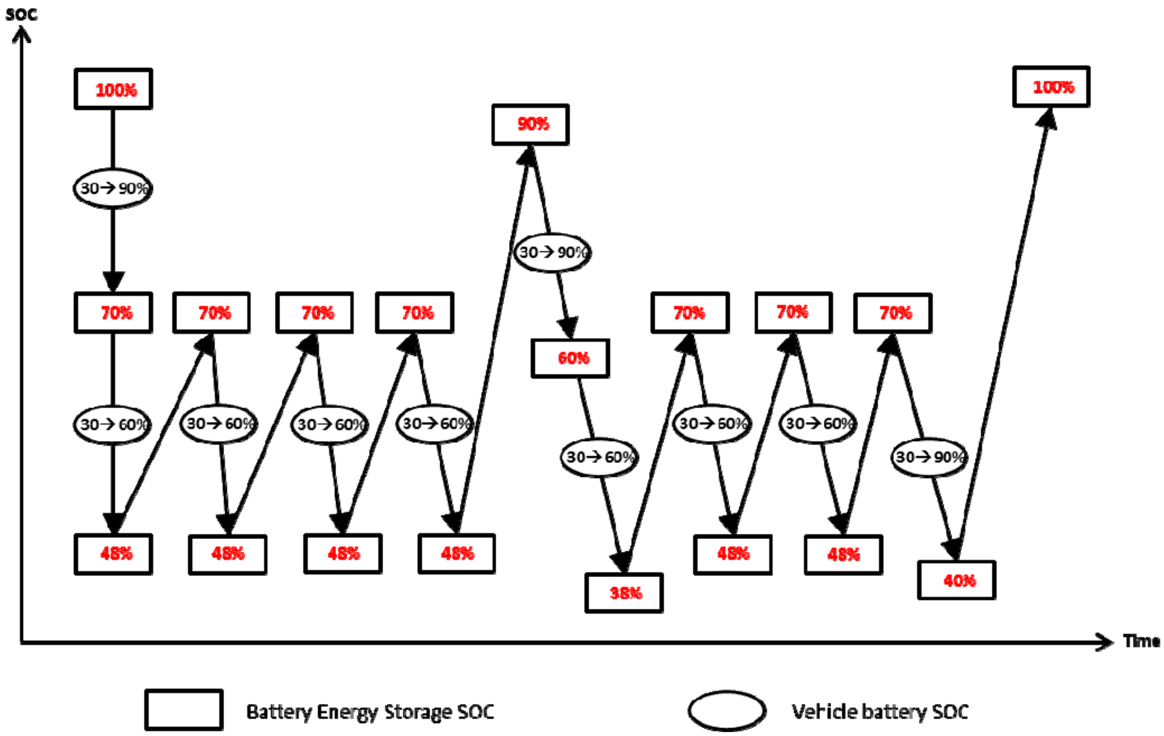

Figure 9. State of charge of the battery energy storage battery and vehicle battery during one day of real-time duty under the 20-kWh battery energy storage profile.

Table 4. Energy distribution of various charging scenarios.

Vehicle Battery SOC	Total Energy Required (kWh)	Energy from Battery (kWh)	Energy from Grid (kWh)	BES System Battery SOC Discharge	Estimated Charging Time (minutes)
30 to 60%	7.2	4.3	2.9	22%	8.6
30 to 90%*	11.6	5.9	5.7	30%	24.6

* The 30 to 90% charge data were based on true field test data. The total vehicle battery capacity was 19.3 kWh, which is the actual usable capacity, based on the vehicle battery management system calculation for this particular test.

This pattern of vehicle charge/BES system discharge, followed by a partial recharge of the BES system from the grid, continued until a total of 10 vehicles were charged, which was considered to simulate the duty cycle of one single day. The BES system battery was then fully recharged overnight in readiness for the next day.

As mentioned above, one 6-hour pass through the simulated profile represented 24 hours of duty in the field and provided a time-compression factor of 4:1. It is likely that such a time compression would increase the BES system temperature more than experienced in the field, because during normal duty, the field BES system would experience more rest periods. This situation was an unfortunate side effect of simulations that speed up real-time duty and resulted in shorter lifetimes. However, provided that such simulations are controlled appropriately, useful information is provided on the relative performances of different technologies.

4.4 Task 3.14.4: Performance Metrics for Assessing the Battery Energy Storage System Battery Performance Under the 20-kWh Battery Energy Storage Profile

A series of metrics were identified to provide accurate performance comparisons of different BES system battery technologies operated under the 20-kWh BES profile. These metrics are described in Sections 4.4.1 through 4.4.4.

4.4.1 Metric One - Battery Temperature

The BES system was designed to operate with passive cooling only (i.e., without any air conditioning). Because battery lifetime generally decreases with increasing temperature, and high ambient temperatures are expected in many locations in the summer months, it is important that BES systems experience minimal heating as a result of the actual operating schedule. Accordingly, battery temperature was included as a metric in this study and is presented simply as single lines of data on an x-y graph. Further, temperature limits were provided by the battery manufacturers and programmed into the test cycle. Battery operations were halted if the temperature exceeded the manufacturer's temperature limits. Cycling was restarted when the battery temperature dropped to a lower level. The rise in battery temperature, especially if it occurred continuously during the test cycle, was closely monitored to determine the termination point of the testing.

4.4.2 Metric Two - Voltage Trends

Two voltage parameters that can be used to gauge battery performance are the lowest voltage and the highest voltage observed during a particular duty cycle. The lowest voltage will occur at the end of most severe discharge step and is known as the end-of-discharge voltage (EODV). Similarly, the highest voltage will occur at the end of one of the designated charges and is known as the top-of-charge voltage (TOCV). If monitored continuously, these two voltages can provide useful comparisons between different battery technologies. Accordingly, EODV and TOCV were recorded for the duration of the testing.

4.4.3 Metric Three - Capacity

Changes in capacity recorded at a standard rate also were useful for determining the rate of performance loss. Therefore, the battery capacity was tested periodically at a standard rate and was recorded during operation under the 20-kW BES profile.

4.4.4 Metric Four – Operating Efficiency

The operating efficiency of batteries is an important parameter, because it provides information on the energy requirements and costs during operation, which often change as batteries age. In this study, the operating efficiency was obtained by plotting Wh versus Ah over each pass through of the 20-kW BES profile. Because the duty was scaled as if the module was performing in an entire pack, the Wh versus Ah chart provided a very simple, visual guide showing the battery wasted more energy during both charge and discharge over the entire screening test period. Also, how thick the line is tells us if the efficiency changed during the test. A thin line means the values are the same for each cycle and experienced no change. A thick line means the efficiency changed noticeably.

4.5 Task 3.14.5: Validation of the 20-kWh Battery Energy Storage Profile

The following three lithium battery technologies were operated under the 20-kWh profile and the results are summarized in terms of the performance metrics described in Section 4.4. The Sony/US26650FT and A123/ANR26650MIA battery technologies performed well for the 3-month cycling period, but the Panasonic/NCR18650 battery technology failed after just 19 days.

- A123/ANR26650MIA lithium ion phosphate - 2.3 Ah cell
- Sony/US26650FT lithium ion phosphate - 2.85 Ah cell
- Panasonic/NCR18650 - 2.75 Ah cell.

4.5.1 Metric One - Battery Temperature

The naked cells were operated in the laboratory (without any packaging) at an ambient temperature of 25°C. Thus, the observed operating temperatures are considered to represent the average ambient temperatures likely to be encountered in the field.

The temperatures of the three batteries during cycling are summarized in Figure 10. The temperatures of both the Sony/US26650FT and A123/ANR26650MIA battery technologies are very similar and remained constant during the 3-month cycling period. In addition, the temperature increased as a result of cycling by only 2°C. By contrast, the temperature of the Panasonic/NCR18650 battery technology increased by more than 15°C in 19 days. This increase is considered excessive. Because it is planned to operate the BES system with passive cooling (i.e., no air conditioning) at an ambient temperature of 40°C, the operating temperature of the Panasonic/NCR18650 battery technology would be at least 55°C in less than 20 days of operation. Obviously, this technology is not considered suitable for continuous high-rate operation. Therefore, it is recommended for the test profile that the temperature rise during the BES duty cycle be limited to a 10°C increase, especially if the battery temperature gives a trend of a steady, continuous increase.

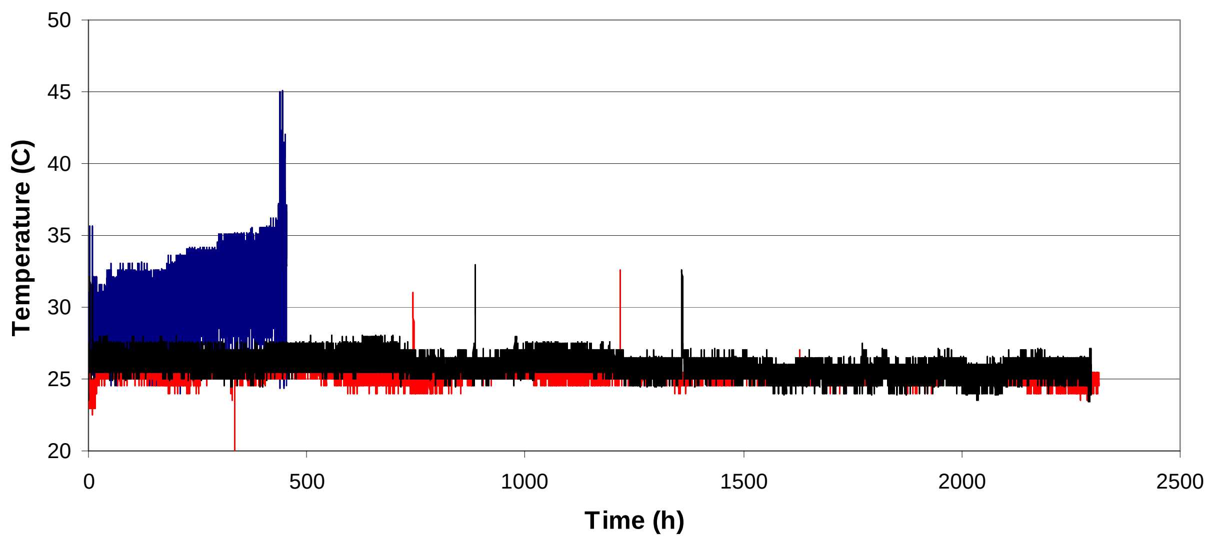

Figure 10. Temperature of Sony/US26650FT (Black Line), A123/ANR26650M1A (Red Line), and Panasonic/NCR18650 (Blue Line) battery technologies operating under the 20-kWh battery energy storage profile.

4.5.2 Metric Two - Voltage Trends

How the operating voltage of a battery subjected to repetitive cycling changes with time provides important information on performance of the technology. A convenient way to analyze this trend is to record TOCV and EODV. This information was collected for the A123/ANR26650MIA, Sony/US26650FT, and Panasonic/NCR18650 battery technologies and is summarized in Figures 11 through 13. At the start of duty, the extent of the voltage spread (i.e., TOCV-EODV, designated as ΔV) was smallest for the A123/ANR26650MIA battery technology (Figure 11) and largest for the Panasonic/NCR18650 battery technology (Figure 13). As cycling progressed, the ΔV of the

A123/ANR26650MIA and the Sony/US26650FT battery technologies remained relatively constant, whereas that of the Panasonic/NCR18650 battery technology increased quickly. This trend continued until the Panasonic/NCR18650 battery technology failed to maintain EODV above the manufacturer recommended discharge voltage limit after just 19 days of duty. Figures 14 and 15 show the short duration view of the voltage profile for the A123/ANR26650MIA and Panasonic/NCR18650 battery technologies operating under the BES profile.

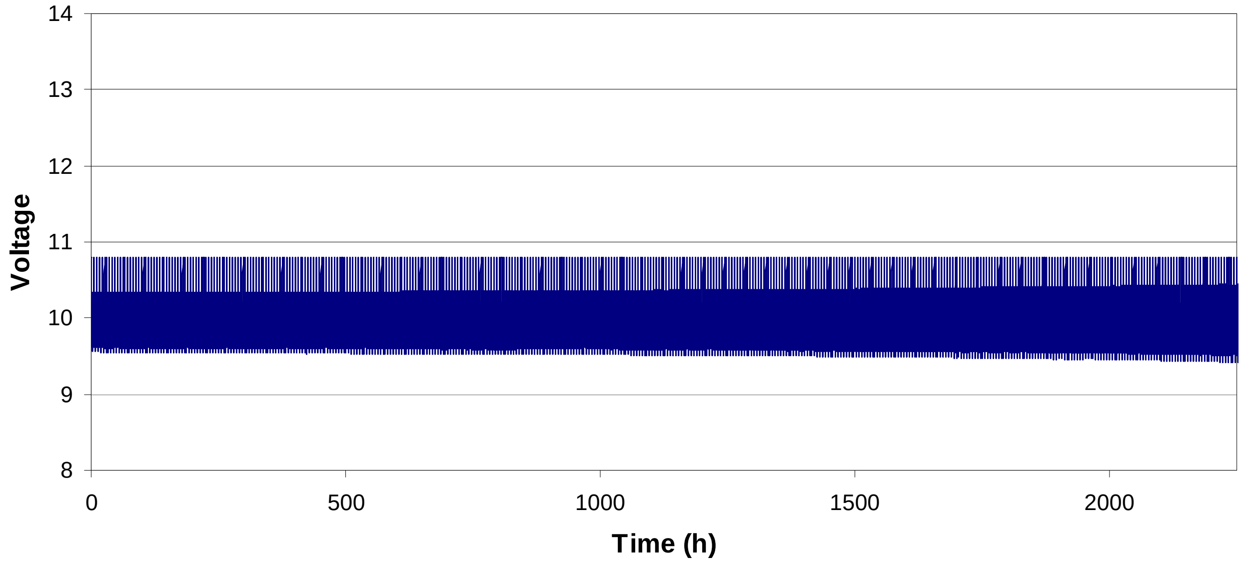

Figure 11. Voltage of the A123/ANR26650M1A battery technology operating under the 20-kWh battery energy storage profile.

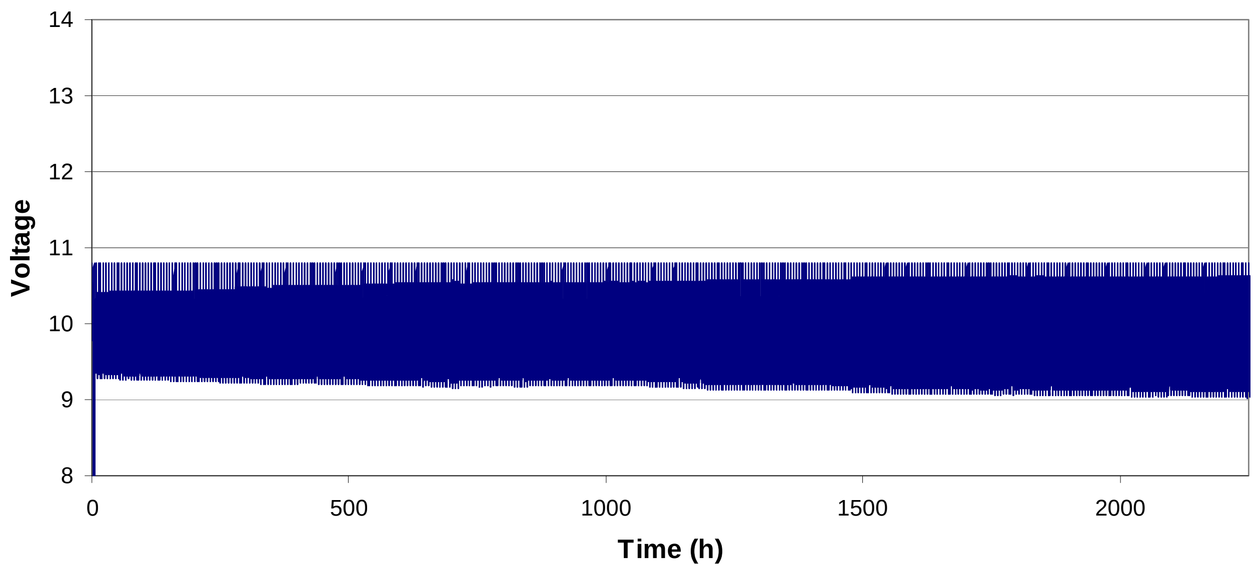

Figure 12. Voltage of the Sony/US26650FT battery technology operating under the 20-kWh battery energy storage profile.

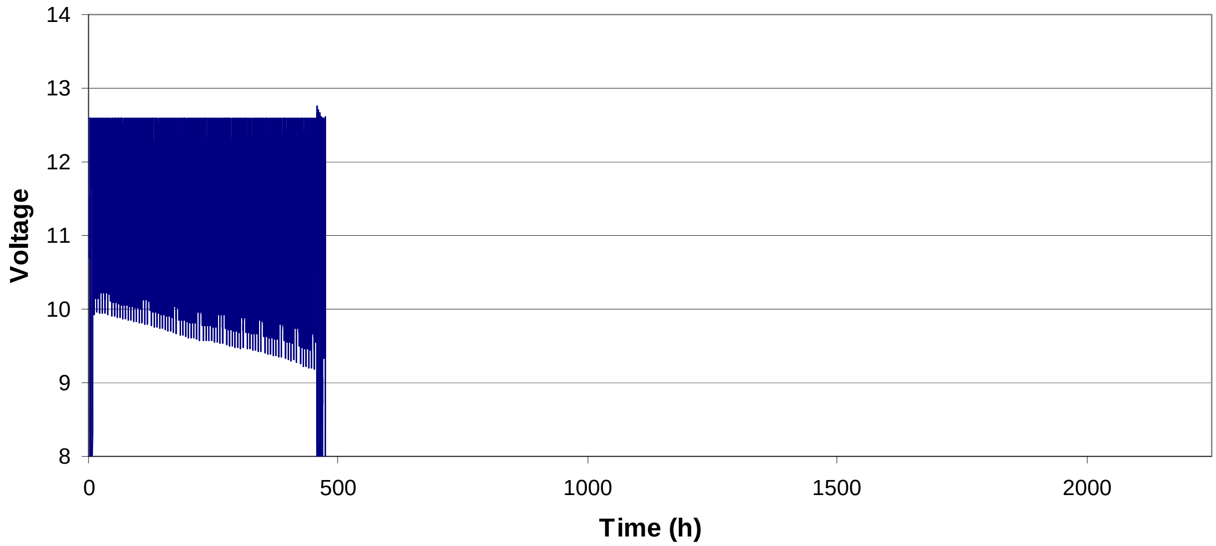

Figure 13. Voltage of the Panasonic/NCR18650 battery technology operating under the 20-kWh battery energy storage profile.

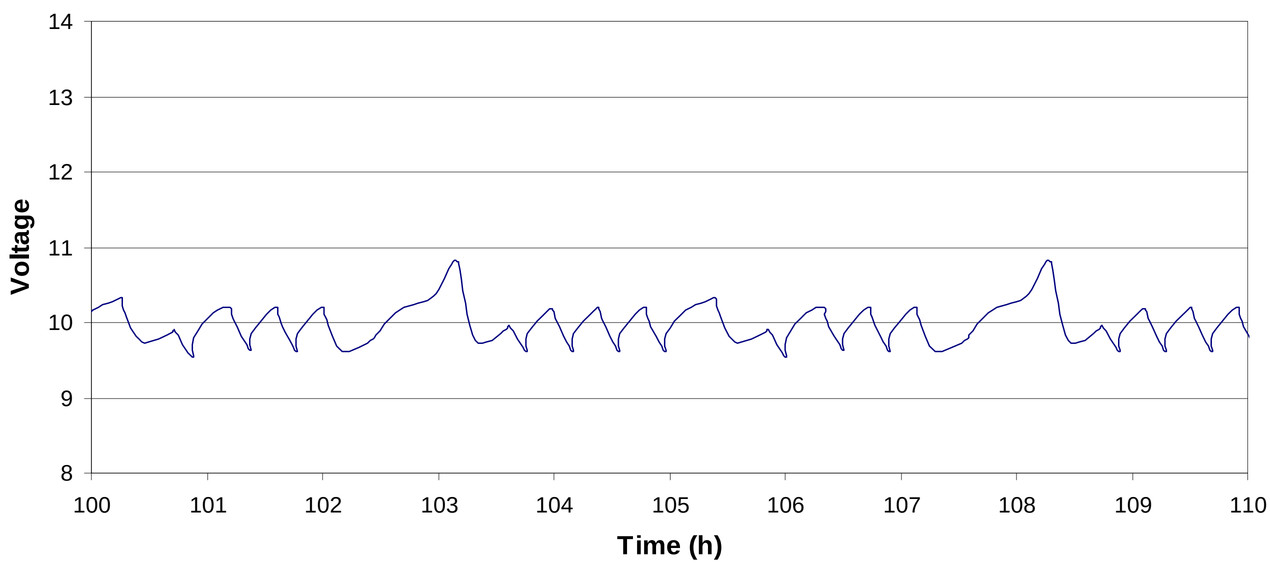

Figure 14. Short duration view of voltage of the A123 battery technology operating under the 20-kWh battery energy storage profile.

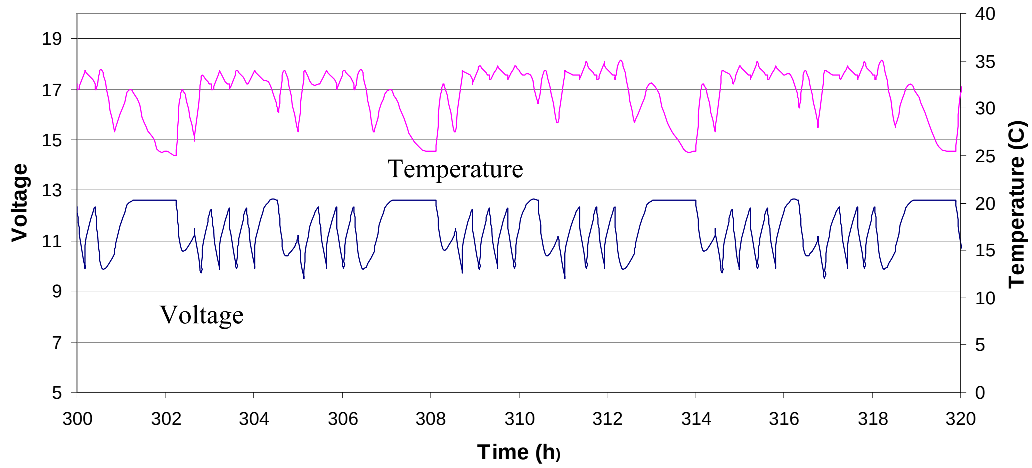

Figure 15. Short duration view of voltage and temperature of the Panasonic/NCR18650 battery technology operating under the 20-kWh battery energy storage profile.

4.5.3 Metric Three - Capacity

The battery capacity was tested periodically at a standard rate. The capacity (1C rate) of the technologies after cycling is shown in Table 5. It should be noted that the A123/ANR26650MIA and Sony/US26650FT battery technologies experienced a similar level of degradation after 3 months of cycling (86% and 88% of initial capacity, respectively), but the Panasonic/NCR18650 battery technology dropped to 72% after just 19 days.

Table 5. Capacity of normal batteries versus after 3 months of the 20-kWh battery energy storage profile test.

Technology	Nominal Capacity (Ah, 1C rate)	Measured Capacity (Ah, 1C rate)	Capacity After 3 Months on Profile (Ah, 1C rate)	Percentage of Initial Capacity After Cycling (%Ah, 1C rate)
A123/ANR26650M1A	2.30	2.21	1.91	86[a]
Sony/US26650FT	2.98	2.96	2.61	88[a]
Panasonic/NCR18650	2.75	2.84	2.04	72[b]

[a] After 90 days of duty
[b] After 19 days of duty

4.5.4 Metric Four – Operating Efficiency

The operating efficiency of a technology is important, because it defines the amount of energy available during discharge and the cost to recharge.

Representations of the charging efficiency for the three battery technologies were obtained by plotting Wh versus Ah for each individual charge and discharge step completed during operation under the 20-kWh BES profile, respectively (Figure 16). Once again, the charge efficiency of both the A123/ANR26650MIA and Sony/US26650FT battery technologies are closely matched, whereas the Panasonic/NCR18650 battery technology required considerably more energy to return an equivalent number of Ahs.

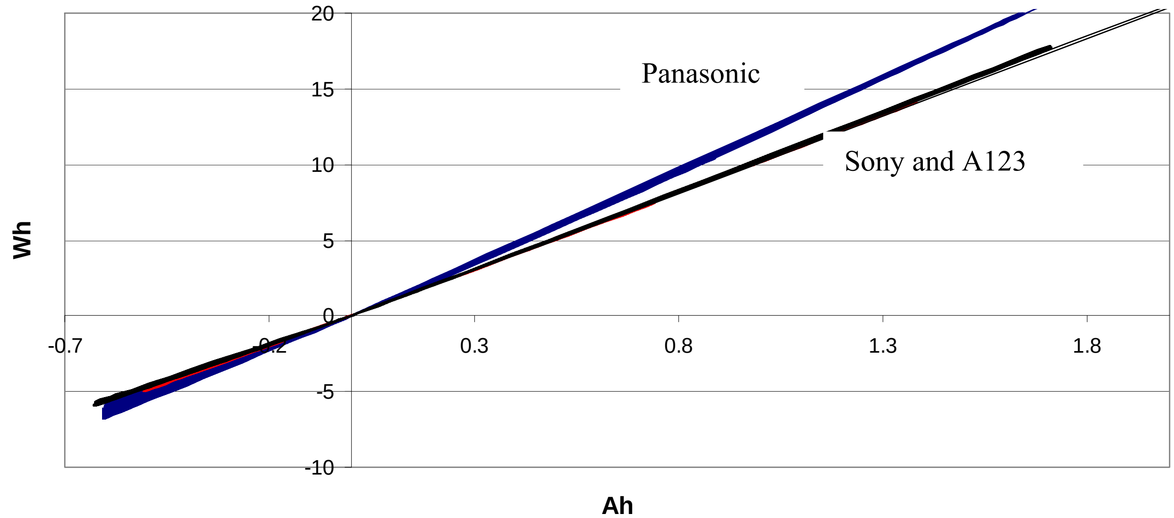

Figure 16. Wh versus the Ah for the three battery technologies during operation under the 20-kWh battery energy storage system.

4.6 Task 3.14.6: Develop and Validate a Test Profile for Evaluating Battery Performance in a 200-kWh Battery Energy Storage System

4.6.1 Test Profile for Evaluating Battery Performance in a 200-kWh Battery Energy Storage System

A profile that simulated operation of a 200-kWh battery in a BES system was developed and termed the 200-kWh BES profile. All power (i.e., 50 kW) required for the vehicle charge was provided by this BES system, because it was assumed that no grid power would be available during the daytime. Consequently, the 200-kWh BES system was only recharged at night with off-peak electricity (i.e., no opportunity-charging during the day). However, it could charge vehicles continuously, one at a time, during the daytime. By contrast, vehicles being charged by a 20-kWh BES system may need to wait for the BES system itself to be recharged. Also, the rate of discharge, in comparison to battery capacity, required from the 200-kWh BES system for charging vehicles is one tenth of that experienced by the 20-kWh BES system. Therefore, the operating temperature of the larger system will always be close to ambient. The major disadvantage of the 200-kWh BES system is that its initial capital cost will be much higher than that of the 20-kWh BES system.

The simulated 200-kWh BES profile employs the same discharge pattern as the 20-kWh BES profile; one vehicle charge from 30 to 90% SOC (requiring 14.4 kWh from the BES system) followed by four vehicle charges from 30 to 60% SOC (each requiring 7.2 kWh from the BES system) and is continued until the SOC for the BES system drops below 35%. The profile is summarized in Table 6.

4.6.2 Validation for the 200-kWh Battery Energy Storage Profile

Three A123/ANR26650MIA cells, in series, were operated under the 200-kWh BES system in order to validate the procedure, with specific charge and discharge currents applied in order to simulate duty in a full-sized pack. Because the operating conditions of the battery are far less rigorous with this system than with the 20-kW BES system, only one cell type was tested to provide baseline data for and validation of the procedure. The voltage response of the string during operation is shown in Figures 17 and 18, and it should be noted that the charge pattern began its fourth repeat before the EODV limit was reached (i.e., 9.6 volts at approximately 35% SOC; Figure 17). This means that when the BES system is new, it is capable of recharging 15 vehicles during the day before it requires a full charge itself (which occurred only once a day, at night time, with off-peak electricity).

Table 6. State of charge for the 200-kWh battery energy storage system during one duty day.

Vehicle Charge (%)	BES System SOC Start (%)	BES System SOC End (%)
30 to 90	95	87.8
30 to 60	87.8	84.2
30 to 60	84.2	80.6
30 to 60	80.6	77.4
30 to 60	77.4	73.8
30 to 90	73.8	66.6
30 to 60	66.6	63
30 to 60	63	59.8
30 to 60	59.8	56.6
30 to 60	56.6	53.5
30 to 90	53.4	46.2
30 to 60	46.2	43
30 to 60	43	39.8
30 to 60	39.8	36.6
30 to 60	36.6	33.4
Off peak charge	33.4	95

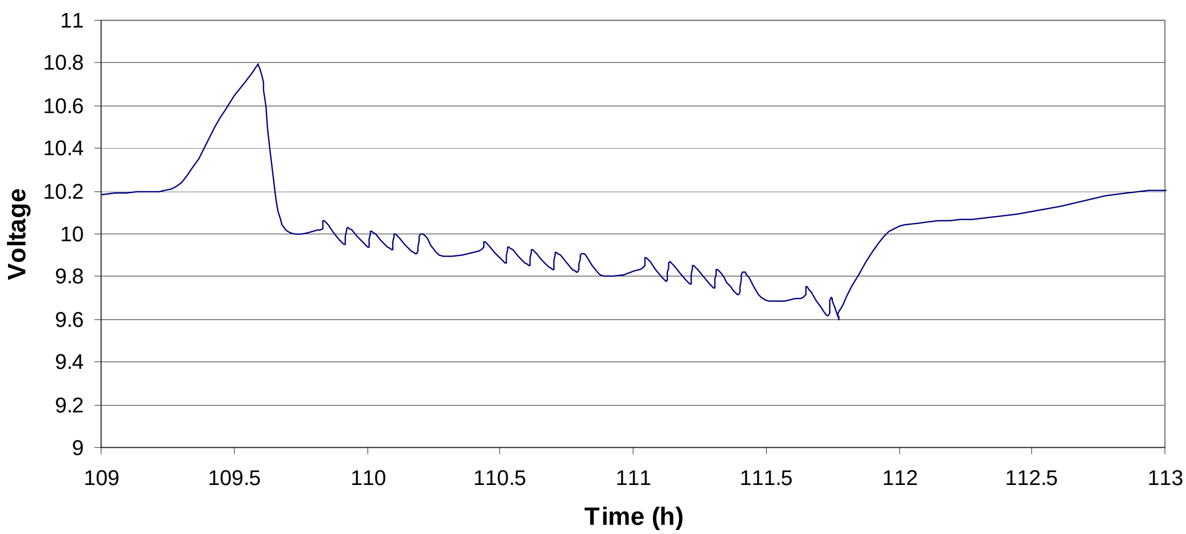

Figure 17. Voltage of A123/ANR26650M1A battery technology operating under the 200-kWh battery energy storage profile (one day of simulated operation).

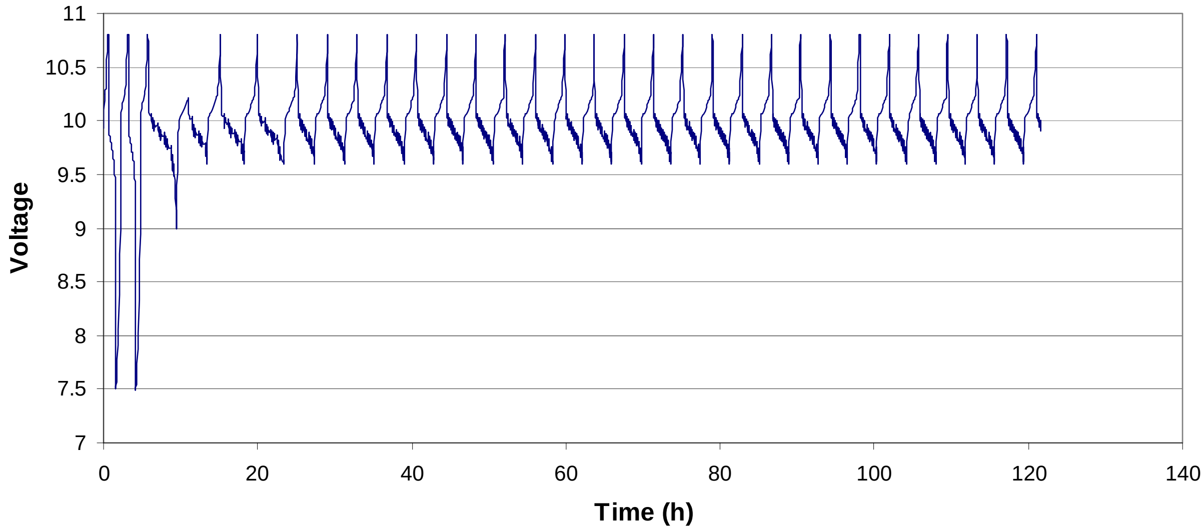

Figure 18. Voltage of A123/ANR26650M1A battery technology operating under the 200-kWh battery energy storage profile.

5. SUMMARY

In this project, two laboratory simulation profiles were developed to evaluate battery performance under two different BES systems for demand reduction on DCFC units.

The first simulated BES profile was based on the assumption that battery storage only had a capacity of 20 kWh. The power required for the vehicle recharge was co-supplied by the grid (20 kW maximum to avoid the demand charge) and the ground storage battery (30 kW). The BES system had the chance to be recharged by the grid at 20 kW when a vehicle was not charging.

The second simulated BES profile was based on the assumption that battery storage would be the sole power supply for the vehicle charge. The grid power was not available during the day. The ground storage battery itself could only be recharged during the night, when off-peak electricity was available. Therefore, the second BES system had a much larger capacity at 200 kWh.

Both test profiles were validated. Performance metrics, which include battery temperature, battery voltage (especially TOCV and EODV trend), battery capacity, and operating efficiency, were developed to assist the performance comparisons among the different battery technologies. Three different lithium battery technologies, Sony/US26650FT, Panasonic/NCR18650 and A123/ANR26650M1A, were operated under the simulated 20-kWh BES profile for 3 months. The Panasonic/NCR18650 technology failed after 19 days, whereas the Sony/US26650FT and the A123/ANR26650M1A technologies were at 88% and 86% of their initial capacities, respectively, at the end of the 3-month test. The relatively higher operating temperatures, voltage drop, and internal resistance of the Panasonic/NCR18650 battery technology suggested that it is not as well suited for the high-rate BES system compared to the evaluated Sony/US26650FT and A123/ANR26650MIA battery technologies.

6. APPENDIX

The test specification for DCFC battery testing referenced in this document is attached as the following pages of this appendix.

AVTA Test Specification

Energy Storage for DC Fast Chargers

ECOtality North America
430 S. 2nd Avenue
Phoenix, Arizona 85003-2418
Phone: (602) 716-9576
Fax: (602) 443-9007
www.ecotalityna.com

Initial Issue

October 18, 2012

Document Information

Previous Document(s): None

Standard/Purpose of the Test: Evaluation of battery types available for use as an energy storage unit in conjunction with a DC fast charger.

Rev #	Changes Made	Editor
1	Removed references to internal documents.	Jeff Wishart, Joel Danforth

Prepared by: ______________________ **Date:** **10/18/2012**

(Sally Sun)

Approved by: ______________________ **Date:** **10/18/2012**

(Donald B. Karner)

Electric Transportation Engineering Corporation
dba **ECOtality North America**
430 S. 2nd Avenue
Phoenix, Arizona 85003-2418
(602) 716-9576
www.ecotalityna.com

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1 Objective

The objective of this Test Specification is to provide a process to evaluate various battery types and sizes for the Battery Energy Storage (BES) unit that is to be paired with direct current (DC) fast charge (DCFC) units for the purpose of cost-effective mitigation of electric utility demand charges incurred during DC fast charging. The process models two different operating scenarios of a DCFC unit utilizing energy storage: 1) a small battery pack with an approximate energy capacity of 20 kilowatt-hours (kWh), and 2) a large battery pack with an approximate energy capacity of 200 kWh. Two separate test procedures were developed for each scenario.

2 Purpose

The purpose of this Test Specification is to provide a method for evaluating the performance of potential batteries to be implemented in the BES unit. The effectiveness of each type of battery candidate will be measured based on short-term and long-term performance in ambient conditions. BES units are used to avoid several issues associated with the significant intermittent load that electric vehicle (EV) fast-charging facilities add to the grid.

3 Documentation

Documentation addressed by this Test Specification shall be consistent, easy to understand, easy to read and readily reproducible. Review and approval of test documentation shall be in accordance with appropriate quality control procedures. Storage and retention of records during and following testing activities shall be completed in accordance with appropriate document control procedures.

4 Initial Conditions & Prerequisites

Prior to conducting any portion of testing, the following initial conditions and prerequisites shall be met.

4.1 Personnel

Personnel conducting testing under this Test Specification shall be familiar with the requirements of this Test Specification, and shall be fully trained and certified by the Test Manager prior to commencing any testing activities.

4.2 Manufacturer Information

The tests and conditions outlined in Section 5 are based on the manufacturer's specifications of the battery. Therefore, the following information shall be obtained from the manufacturer:

- Nominal capacity
- Nominal voltage
- Recommended charge rate
- Recommended charge voltage when charging the battery at the recommended charge rate
- Recommended cut-off current when charging the battery at the recommended charge rate
- Recommended charge voltage adjustment due to battery temperature
- Recommended discharge rate
- Recommended discharge cut-off voltage
- Recommended charge operating temperature
- Recommended discharge operating temperature

The following additional information is helpful, but not mandatory:

- Maximum charge current
- Peak discharge current
- Continuous discharge current
- Life cycle
- Cell dimension
- Cell weight

4.3 Test Conduct

- Any deviation from the test procedure and the reason for the deviation shall be recorded in accordance with the appropriate quality control procedures.
- All documentation required to complete testing shall be completed, approved and ready for issue prior to commencing the testing it addresses.
- Distribution, retention and destruction of all test documents shall be in accordance with the appropriate document control procedures.

5 Test Activity Requirements

This section addresses all test types required to meet the stated purpose and objectives of this Test Specification.

5.1 General Test Conditions

- Units of charge and discharge: The charge and discharge of batteries in all test profiles will be based on current, with units of amperes (A). Negative current will correspond to a discharge and positive current will relate to a charge.
- Ambient temperature control: The ambient temperature for all testing shall be controlled at a nominal temperature of 25 °C. All tests shall be preceded by an 8-hour soak at this temperature.
- Battery temperature control: The battery temperature must be monitored, at least, on or inside the battery, where the largest thermal rise is likely to occur and the test must stop if the battery temperature rises above the manufacturer's recommended maximum charging temperature. If a maximum charging temperature is unavailable, a reasonable temperature for the type of battery being charged shall be chosen. It is recommended that cooling techniques applied to the battery during normal operation be used during testing. If these techniques are not enough to sufficiently cool the battery, additional cooling may be used, but a note must be made in the test documentation.
- Battery cycler calibration: The overall error of the battery cyclers in measuring and recording shall not exceed ±2% of the maximum value of the variable being measured. Periodic calibration shall be performed and documented to ensure the compliance with this requirement.

5.2 Collected Test Data

The following data shall be collected for the analysis:

1. Battery voltage, shown as volts (V) versus time
2. Battery current, shown as amperes (A) versus time
3. Battery power, shown as watts (W) versus time
4. Battery capacity, shown as ampere-hour (Ah) versus time
5. Battery energy, shown as watt hour (Wh) versus time
6. Battery temperature, shown as degrees Celsius (°C) versus time
7. Ambient temperature, shown as degrees Celsius (°C) versus time

5.3 Test Descriptions

The following methods and procedures denote battery tests that produce data relative to BES units that are used in conjunction with DCFCs. The tests focus on a battery's performance over a simulated three-month test cycle in order to create a small-scale replication of the battery's expected performance as part of a BES unit. After performance testing and data collection, the cycle profiles of the battery candidates will assist in developing an overall understanding of how various battery technologies may function in the field under ambient conditions.

5.3.1 Characterization of Battery Candidates

The characterization of battery candidates helps predict a battery's performance when used to fast charge EVs in conjunction with the grid. The method is predictive in nature, does not involve life-cycling of batteries, and can provide useful information in a matter of days. Below is a summary of the process.

(a) Select and assemble a configuration of individual cells that has appropriate voltage/current/power specifications for the battery cycler that is used for testing. The batteries should be open to the atmosphere with no insulating effect from packaging.

(b) Measure the internal resistance of the battery over the entire state-of-charge (SOC) range by:

1. Fully charge the battery. The full charging profile shall be set according to the cell chemistry (i.e., lithium-ion, nickel-metal hydride (NiMH), and lead acid chemistry). If the battery temperature exceeds the limits set by the manufacturer, allow the battery to rest at open circuit until the temperature returns to within the manufacturer limits.
2. Discharge the battery at a constant one-hour rated discharge current, C_1, to achieve a 10% SOC decrease of the battery (this should take approximately six minutes).
3. Rest for five seconds at open circuit.
4. Increase the discharge current to C_X (C_X depends on the cycler capability and the battery manufacture's maximum allowed peak discharge rate) for two seconds. Measure the peak-current voltage (V_{PC}) at the end of the step.
5. Stop the discharge. Measure the resistance-free voltage (V_{RF}) after 100 milliseconds. Let the battery sit at open circuit for 10 seconds.
6. Repeat step 2 (see Figure 1) until battery voltages reach the manufacturer-recommended discharge cut-off voltage.
7. Charge the battery to full to complete the test.

The battery internal resistance (r_{dis}) is calculated by using the equation, shown below:

$$r_{dis} = \frac{V_{PC} - V_{RF}}{C_X} \ (\Omega)$$

The discharge current profile is demonstrated in Figure 1. A plot can be drawn to show the battery internal resistance as a function of SOC in 10% increments.

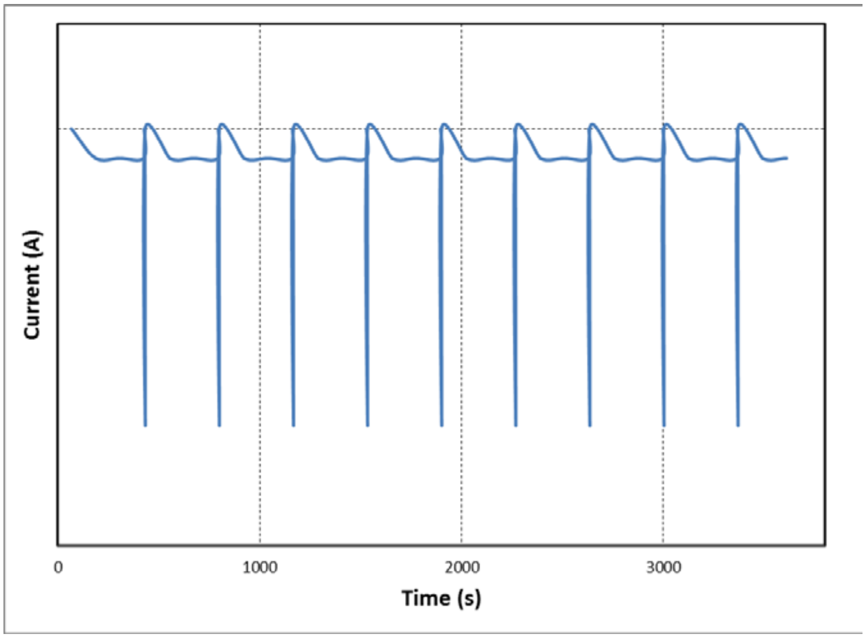

Figure 1. Current Profile for Internal Resistance Measurement

(c) Characterize the batteries discharge performance:

1. Pre-charge the battery. The full charging profile shall be varied to lithium-ion, NiMH and lead acid chemistry. If the battery temperature exceeds the limits set by the manufacturer, allow the battery to rest at open circuit until the temperature returns to within the manufacturer limits.
2. Fully discharge the battery at a 0.5C rate to the manufacturer's recommended discharge cut-off voltage.
3. Fully charge the battery at 1C rate.
4. Repeat Step 2 and Step 3 with the same charge profile, but use three discharge rates: 1C, 1.5C, and 2C. The highest discharge rate (2C) should be adjusted, depending on the current specifications for the battery cycler that is used for testing.
5. Set a rest period between charge and discharge steps to allow the battery to cool down if its surface temperature rises above 28°C.

If the highest discharge rate (2C) exceeds the current specifications for the battery cycler that is used for testing, it shall be adjusted to the maximum current capacity of the cycler.

The battery surface temperature shall be collected for both the charging and discharging characterization tests by attaching a thermocouple to the external surface of the battery under an approximately 1 cm^2 thermal insulation pad.

The current profile for the battery discharge performance test is shown in Figure 2.

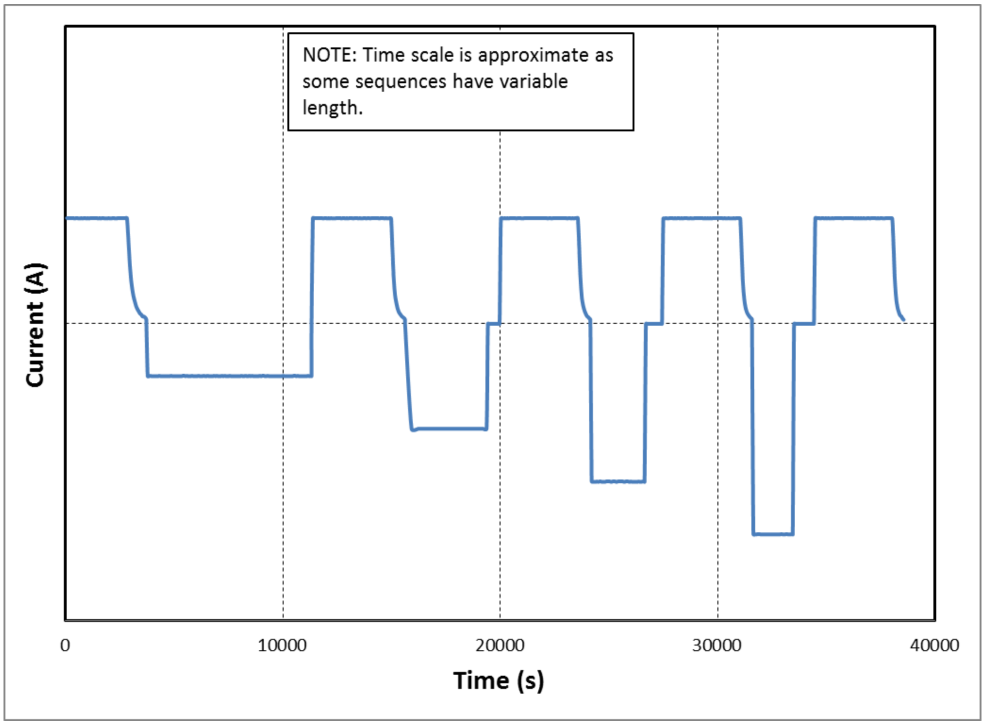

Figure 2. Current Profile for Battery Discharge Performance Test

(d) Characterize the batteries' charge performance

1. Pre-charge the battery. The full charging profile shall be varied to lithium-ion, NiMH and lead acid chemistry. If the battery temperature exceeds the limits set by the manufacturer, allow the battery to rest at open circuit until the temperature returns to within the manufacturer limits.
2. Fully discharge the battery at a 1C rate to the manufacturer's recommended discharge cut-off voltage.
3. Fully charge the battery at a 0.5C rate.
4. Repeat Step 2 and Step 3 with the same discharge profile, but use three charge rates: 1C, 1.5C and 2C. The highest charge rate (2C) can be adjusted, depending on the current specifications for the battery cycler tht is used for testing.
5. Set a rest period between charge and discharge steps to allow the battery to cool down if its surface temperature rises above 28°C.

If the highest discharge rate (2C) exceeds the current specifications for the battery cycler that is used for testing, it shall be adjusted to the maximum current capacity of the cycler.

The current profile for the battery discharge performance test is shown in Figure 3.

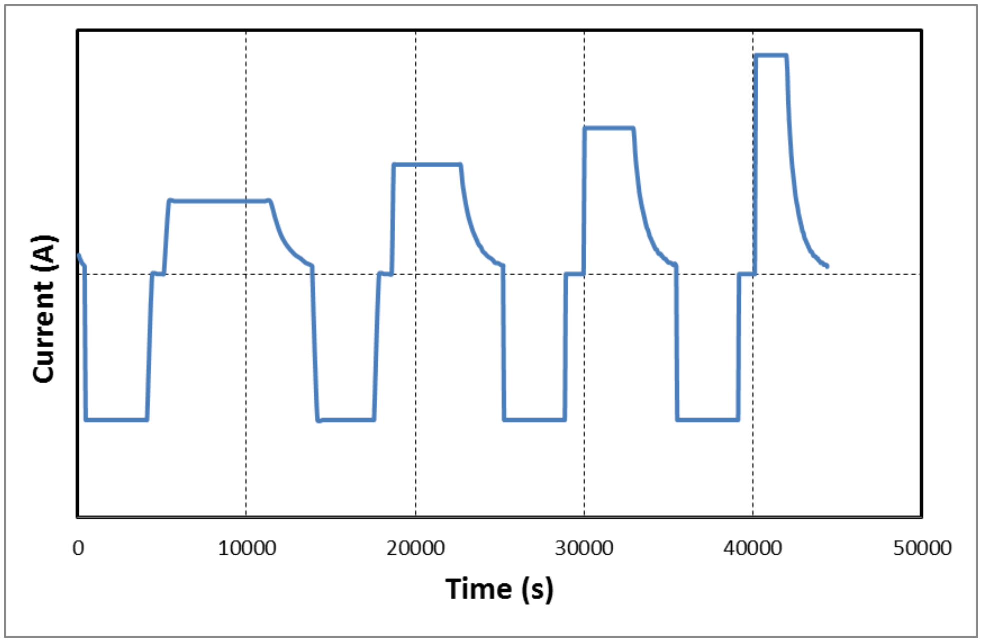

Figure 3. Current Profile for Battery Charge Performance Test

The battery temperature profile, charging and discharging power, current, voltage and energy profiles shall be plotted for these characterization tests.

5.3.2 Evaluation of Battery Performance under the Simulated 20-kWh BES Profile

A BES unit employed to assist the main grid to recharge EVs would experience a wide range of operating conditions, such as the number of vehicles to be charged per day and the level of recharge required.

A test profile, termed the '20-kWh BES profile', with a BES unit that has a useable energy capacity of 20 kWh has been developed. In this profile, the EV battery being charged has a useable energy capacity of 24 kWh. It also assumes that the main grid can contribute up to 20 kW (i.e., demand charges are imposed above 20 kW), with the BES unit providing up to 30 kW. Therefore, 50 kW total is available during recharge, which corresponds to a maximum discharge rate for the BES unit of 1.5C. .

The charge profile, with all of the variables is shown below in Figure 4. In order to visualize the charge profile, it is assumed that there is some time period M at which the BES provides its maximum power (in blue) such that the total charge power is P, and further that period corresponds to the vehicle battery charge from 30% to 60% (shown in red). At the end of this period, the charge power reduces non-linearly to a minimum value N, at which point the charge ends with the vehicle battery at 90% SOC. The BES provides power for the portion of the charge where the total power is above 20 kW. The grid provides the rest of the charge energy. The grid power thus reduces from its maximum of 20 kW to the minimum charge power N. It should be noted that rests between charging and discharging are minimized to allow a complete 24-hour day to be compressed into approximately six hours.

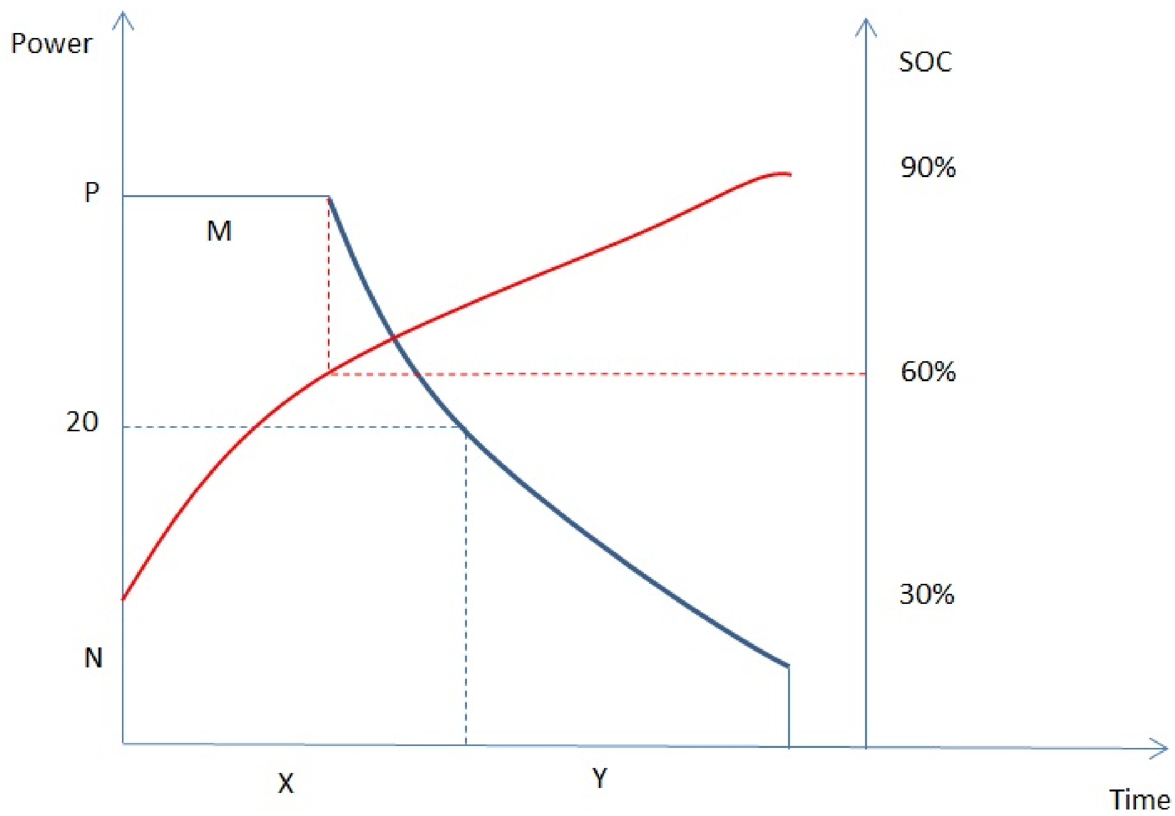

Figure 4. BES-DCFC Power and SOC versus Time for a Simulated Vehicle Charge

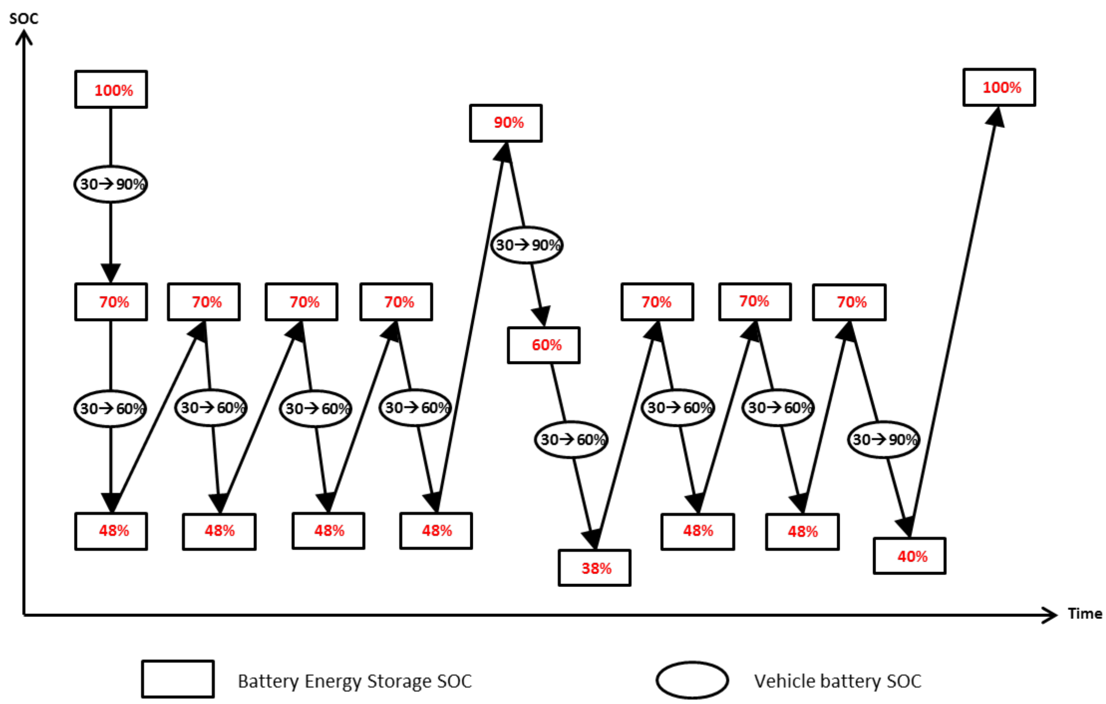

Figure 5. SOC of BES Unit and Vehicle Battery During a Single Day of Real-time Duty under the 20 kWh BES Profile

Figure 5 illustrates an assumed typical day for the BES-DCFC unit operation. The BES-DCFC unit starts the day at 100% SOC. It then recharges a vehicle battery from 30% to 90% SOC and in the process, the BES-DCFC unit is discharged at the 1.5C rate from 100% to 70% SOC. The second vehicle is then recharged from 30% to 60% SOC, during which time the BES unit is discharged from 70% to 48%. The BES-DCFC unit is then recharged from 48% to 70% from the grid at the 1C rate, and is then ready to recharge the next vehicle battery.

This pattern of vehicle charge/BES-DCFC unit discharge, followed by a partial recharge of the BES-DCFC unit from the grid continues until a total of 10 vehicles have been recharged (seven minor EV recharge events, 30% to 60% SOC, and three moderate EV recharge events, 30% to 90% SOC), which is considered to equate to one day's duty. The battery is then fully charged overnight in readiness for the next day's duty.

5.3.3 Evaluation of Battery Performance under the Simulated 200-kWh BES Profile

A second test profile, termed the '200-kWh BES profile', with a BES unit that has a useable energy capacity of 200-kWh has also been developed. A profile that simulates operation of a 200-kWh battery in a BES system assumes all the power (up to 50 kW) required for the vehicle charge will be provided by this BES system as no grid power will be available during the daytime. Consequently, the 200-kWh BES system is only charged at night with off-peak electricity, thus, there is no opportunity charging during the day. However, the BES-DCFC system can charge vehicles continuously, one at a time, during the day.

The discharge pattern that this simulated 200-kWh BES profile employs is one vehicle charge from 30% to 90% SOC followed by four vehicle charges from 30% to 60% SOC. The profile is summarized in Table 1, and is continued until the SOC of the BES system drops below 35%.

Table 1. SOC of 200 kWh BES System During One Duty Day

Vehicle Charge Event Number	Vehicle Charge (%)	BES SOC Start (%)	BES SOC End (%)
1	30 to 90	95.0	87.8
2	30 to 60	87.8	84.2
3	30 to 60	84.2	80.6
4	30 to 60	80.6	77.4
5	30 to 60	77.4	73.8
6	30 to 90	73.8	66.6
7	30 to 60	66.6	63.0
8	30 to 60	63.0	59.8
9	30 to 60	59.8	56.6
10	30 to 60	56.6	53.5
11	30 to 90	53.4	46.2
12	30 to 60	46.2	43.0
13	30 to 60	43.0	39.8
14	30 to 60	39.8	36.6
15	30 to 60	36.6	33.4
	Off-peak charge	33.4	95.0

5.3.4 Performance Metrics for Assessing Performance under the 20-kWh and 200-kWh BES Profiles

A series of metrics have been identified to provide accurate performance comparisons of different battery technologies operating under the 20-kWh and 200-kWh BES profiles. These metrics are described as follows.

- **Metric one – Battery temperature**

  As the BES-DCFC units are planned to operate with passive cooling only, and without air-conditioning, high operating temperatures are expected in many areas in the summer months. Since the battery lifetime generally decreases with increasing temperature, it is important that BES batteries experience minimal heating as a result of the actual operating schedule. Accordingly, battery temperature is included as a metric, and is presented simply as single line of data on an x-y graph. The battery temperature rise, especially if it occurs continuously during cycle, shall be closely monitored to determine the termination point of the testing.

- **Metric two – Voltage trends**

  Two parameters that can be used to gauge battery performance are the lowest voltage and the highest voltage observed during a particular duty cycle. The lowest voltage will occur at the end of one of the discharges, and thus is known as the end-of-discharge voltage (EODV); similarly, the highest voltage will occur at the end of one of the charges, and is thus known as the top-of-charge voltage (TOCV). If monitored continuously, these two voltages can provide useful comparisons between different battery technologies. Accordingly, the EODV and TOCV shall be recorded during operation under the test profiles for the duration of the testing.

- **Metric three - Capacity**

  Changes in capacity recorded at a standard rate are also useful for determining the rate of performance loss. Therefore, the battery capacity shall be tested periodically at a standard rate and was recorded during operation under the test profiles for the duration of the testing.

- **Metric four – Operating efficiency**

  The operating efficiency of batteries is an important parameter, as it provides information on the energy requirements and costs during operation, which often change as batteries age. In this test, the operating efficiency is obtained by plotting Wh versus Ah over each pass through of the test profile. As the duty is scaled as if the module is performing in an entire pack, the Wh versus Ah chart provides a very simple visual guide as to which battery wastes more energy during both charge and discharge over the entire screening test period. Also, how thick the line is tells us if the efficiency changes during the test. A thin line means the values are the same for each cycle and no change. A thick line means the efficiency has changed noticeably.

6 Glossary

Battery Energy Storage (BES): An energy storage unit developed to reduce the power demand required by a DC fast charging station for electric vehicle charging.

Effective Date: After a procedure has been reviewed and approved, the first date the procedure can be utilized for official data collection and testing.

Initial Conditions: Conditions that must exist prior to an event occurring.

Prerequisites: Requirements that shall be met or resolved prior to an event occurring.

Shall: This word is used to indicate an item which requires adherence without deviation. 'Shall' is used to identify the binding requirements in a statement. A go or no-go criterion.

Should: This word is used to identify an item, which requires adherence if at all possible. 'Should' statements identify preferred conditions.

State of Charge (SOC): The SOC is defined as the present capacity, (amperes-hours or watt-hours), expressed as a percentage of the total available.

Test Engineer: The individual(s) assigned responsibility for the conduct of any given test.

Test Manager: The individual responsible for the implementation of the test program.