



White Paper

Public-Domain Test Data Showing Key Benefits and Applications of the UltraBattery®

January 2014

UltraBattery 

Abbreviations Used in this Paper

Abbreviation	Meaning
AC	Alternating current
AEMO	Australian Energy Market Operator
ALABC	Advanced Lead Acid Battery Consortium
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DC-DC	To describe efficiency from direct current (DC) input to DC output
DoD	Depth of discharge
DOT	U.S. Department of Transportation
EUCAR	European Council for Automotive R&D
FCAS	Frequency control ancillary services
Diesel genset	Diesel generator set
HEV	Hybrid electric vehicle
Hz	Hertz (cycles per second)
IATA	International Air Transport Association
ISS	Idling-stop-start
kW	Kilowatt
Li-ion	Lithium Ion
mpg	Miles per gallon
MW	Megawatt
NEDO	New Energy and Industrial Technology Development Organization
NiMH	Nickel-metal hydride
PNM	Public Service Company of New Mexico
pSoC	Partial state of charge
PV	Photovoltaic
RAPS	Remote-area power supply
SHCHEVP	Simulated Honda Civic HEV profile
SoC	State of charge
SWER	Single-wire earth return
UPS	Uninterruptible power supply
V	Volt
VRLA	Valve-regulated lead-acid

Acknowledgements

This White Paper has been developed by Ecoult in order to identify the unique aspects of its UltraBattery[®] technology solutions by bringing together the various scientific tests carried out by major independent laboratories and by UltraBattery[®] manufacturers and system developers around the world.

Ecoult acknowledges and appreciates the significant input of scientist, writer and former CSIRO staffer Geoff James, who researched and wrote the original draft and was the leading external contributor to the paper.

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1 Introduction

The UltraBattery[®] is a hybrid energy-storage device that combines a supercapacitor (alternatively called an ultracapacitor) and a lead-acid battery in single-unit cells, incorporating the best of both technologies and balancing their chemical and electrical characteristics passively: that is, without the need for extra electronic controls. The hybridization of the two technologies enhances the power and lifespan of the UltraBattery[®] compared to standard lead-acid batteries.

The result is an excellent multipurpose device, well suited to providing continuous variability management for the grid by operating in a partial state of charge that is also able to provide and absorb charge rapidly during acceleration and braking of a hybrid electric vehicle.

This White Paper has been prepared with a view to increasing awareness and understanding of the potential of this breakthrough technology by summarizing and linking sources of publicly available UltraBattery[®] test information. The data can be easily accessed and considered against the key benefits of the technology and against the market segments in which these benefits are important.

1.1 The Technical Breakthrough

The fundamental innovation of UltraBattery[®] technology, developed by Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), is the introduction of an asymmetric supercapacitor inside a lead-acid battery (both storage methods using a common electrolyte) in a manner that modifies the behavior of the lead-acid battery chemistry to enhance power management and reduce negative plate sulfation (Figure 1).

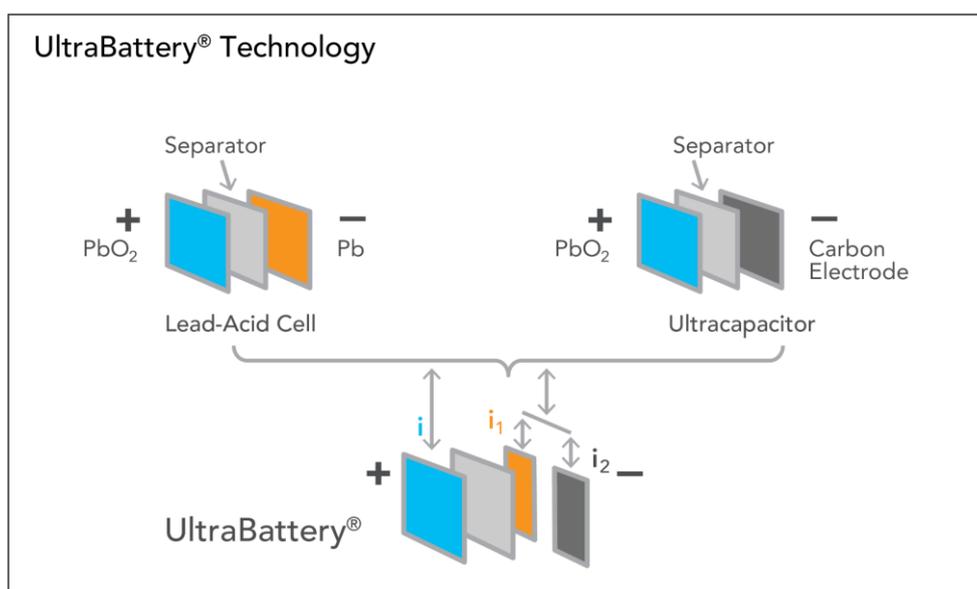


Figure 1: Schematics of standard lead-acid cell (top left), supercapacitor (top right) and their combination in the UltraBattery[®] cell (bottom)

The reduction of the rate of negative plate sulfation, which is the dominant cause of aging of valve-regulated lead-acid (VRLA) batteries when used in high-rate partial state of charge (pSoC), is achieved in UltraBattery[®] cells as an outcome of the carbon-based supercapacitor both being in parallel and sharing a common electrolyte with the negative electrode of the lead-acid cell.

1.2 UltraBattery[®] Testing Programs

The UltraBattery[®] breakthrough was quickly recognized for its potential to provide a safe and recyclable low-cost storage technology with existing mass-production facilities that could be used for active grid energy storage, electric and hybrid electric vehicles and renewable smoothing. Testing very quickly commenced in a wide number of government and commercial laboratories in the USA, Japan and Australia.

It was soon realized that the properties of the UltraBattery[®] supported outperformance across the full range of applications, and that this storage technology could provide solutions for both high-rate pSoC applications (such as renewable smoothing and grid ancillary services including voltage and frequency support) and for energy-shifting applications.

Of considerable further importance was the discovery that the supercapacitor and the lead-acid cell complemented each other in ways that made it possible to support these types of applications *simultaneously*, while additionally maintaining at all times capacity to support reserve events.

That is, an appropriately sized UltraBattery[®] string could be tasked with smoothing the output of a renewable generator, providing grid or microgrid voltage and frequency regulation, and being prepared to deliver a reserve power supply (such as in the manner of a UPS system) against grid outage events, all at the same time.

The first UltraBattery[®] cell produced outside of a laboratory setting was developed and tested in Japan at the Furukawa Battery Company in 2005–06, with the involvement of the CSIRO team including the inventor, CSIRO's Dr Lan Trieu Lam. This program was supported by the New Energy and Industrial Technology Development Organization (NEDO). An internal report (Furukawa & CSIRO, 2008) and company journal article (Furukawa, 2013) summarized the testing outcomes, including field tests in a Honda Insight hybrid electric vehicle (HEV) and at grid-integrated sites for the Kitakyushu Smart Community Creation Project. A journal paper (Furukawa et al., 2010) describes the cell-level and pack-level laboratory tests at the Furukawa Battery Company under several HEV duty cycles.

Three national laboratories in the USA have undertaken independent UltraBattery[®] testing programs for HEV and grid applications. At Idaho National Laboratories, comprehensive cycling tests under simulated HEV profiles (INL, 2012) culminated in retrofitting an UltraBattery[®] pack into a new Honda Civic HEV, which was subjected to dynamometer evaluation at Argonne National Laboratory and then to fleet operation in Phoenix, Arizona, where it accumulates approximately 5000 miles per month under a range of driving conditions (ALABC, 2013).

The Sandia National Laboratories provide reliable, independent, third-party testing and verification of advanced energy storage technologies from cells to MW-scale systems

(Ferreira et al., 2012). With the support of the US Department of Energy, they have demonstrated the longevity of the UltraBattery[®] under low-rate and high-rate cycling. This has resulted in detailed characterization for utility applications (Hund et al., 2008). Additional testing was also done at industry level under programs supported by the Advanced Lead Acid Battery Consortium (ALABC) and US battery manufacturer East Penn Manufacturing, which produces the UltraBattery[®] for both utility and HEV applications.

The longevity, high efficiency and long uptimes envisaged for the battery have been demonstrated in various deployments, often showing results exceeding the initial expectations of the inventors of the technology (such results have included hundred-thousand-mile-plus driving life, many thousands of full capacity cycles, and more than one million pSoC cycles during tests for HEV applications).

Much of the testing of the UltraBattery[®] has been done on a confidential basis by commercial enterprises and as such the results are not available. Nevertheless, a number of sources are in the public domain, and the most significant of these (published before October 2013) have been gathered to support this paper.

There are two major producers of UltraBattery[®] technology holding licenses to manufacture and commercialize the technology in different parts of the world. They are the Furukawa Battery Company (headquartered in Japan) and East Penn Manufacturing (headquartered in the USA). The products of both manufacturers have been subjected to rigorous testing programs, sometimes separately, and sometimes side-by-side in the same laboratory.

In Australia, testing has been supported by the Australian federal government through CSIRO, and by federal and state government grants through the Australian-based UltraBattery[®] solutions developer Ecoult Pty Ltd (now wholly owned by East Penn Manufacturing), at both laboratory level and demonstration scale.

UltraBattery[®] technology has already been successfully implemented in several MW-scale energy storage projects globally, delivering ancillary services, wind and solar smoothing and energy shifting. Initial test results and system outputs show the ability of UltraBattery[®] technology to deliver ancillary services more efficiently and economically than incumbent gas peakers, to successfully manage the ramp rate of large renewable energy plants, and to seamlessly combine renewable energy sources with a storage system.

The Public Service Company of New Mexico (PNM), the leading electric utility company in New Mexico, USA, has in collaboration with energy storage provider Ecoult, integrated an UltraBattery[®]-based storage system with a photovoltaic solar energy plant to demonstrate smoothing and shifting of volatile solar power and the ability to use the combination as a dispatchable renewable resource. The PNM Prosperity Energy Storage Project, funded with support of the U.S. Department of Energy under the American Recovery and Reinvestment Act of 2009 (ARRA), was the first solar storage facility in the USA to be fully integrated into a utility's power grid. It features one of the largest combinations of battery storage and photovoltaic energy in the USA.

The PNM project has shown that energy shifting and smoothing can be very important to the power grid, particularly in altering the profile of grid-scale renewables. Tests had revealed that the 500 kW New Mexico solar photovoltaic (PV) array experienced ramp rates of 136 kW per second as solar energy was lost to cloud cover. Such large fluctuations in energy output can become unsustainable if renewable penetration increases. UltraBattery[®]

technology has successfully controlled and smoothed this PV output, and is demonstrating the viability of combining PV with a battery-based energy storage system.

Another USA-based project, also funded with support of the U.S. Department of Energy under the ARRA of 2009, has been an energy storage system that provides 3 MW of regulation services on the grid of PJM Interconnection, the largest of 10 Regional Transmission Organizations/Independent System Operators in the USA. The system, developed and integrated by East Penn Manufacturing through its subsidiary Ecoult, is also used for peak demand management, and provides continuous frequency regulation services bidding into the open market on PJM, responding to PJM's fast response signal. Traditionally much slower and less accurate gas-peaker plants are used for this service.

An application focus in Australia has been the use of UltraBattery[®] technology to support renewable energy integration and help maintain stability within island power grids with large renewable energy penetration. Work conducted by Ecoult and CSIRO culminated in a MW-scale facility for smoothing the output of a wind farm, about which several government reports have been published (see, for example, CSIRO, 2012). The success of this demonstration has in turn contributed to a commercial UltraBattery[®] deployment on King Island, a remote community of approximately 1700 people just south of the Australian mainland. The community is powered using a wind/diesel microgrid. Ecoult has developed and installed a 3 MW UltraBattery[®] storage solution for the island.

In Japan, the Furukawa Battery Company has developed UltraBattery[®] technology for HEV application and undertaken several HEV laboratory and field trials, which are discussed below.

Furukawa has also developed pilot and commercial projects for stationary storage applications for the Japanese market, concentrating on small-scale, grid-dispersed storage. It is increasingly likely that distributed storage will be a feature of future grids and, along with MW-scale developments, Ecoult, East Penn Manufacturing and the Furukawa Battery Company continue to develop and enhance UltraBattery[®] systems in the kW range.

Furukawa projects include a storage system for a corporate microgrid (a 'smart' building), which has been developed for Shimizu Corporation. The 500 Ah smart building application uses 163 UltraBattery[®] cells, each rated at 2 V. A 'battery condition watcher' installed in the energy storage system monitors cell voltage, impedance and temperature.

Two load-leveling trials have also recently been established, the first at Furukawa's own Iwaki Factory, where the company has set up a smart grid demonstration of UltraBattery[®] technology to control the factory's demand for electric power. The load-leveling application involves 192 UltraBattery[®] cells, a 100 kW power conditioning system and battery management software. The second trial is a 300 kW smart grid demonstration system of UltraBattery[®] technology using 336 UltraBattery[®] cells (1000 Ah, 2 V), which has been installed in the Maeda area in Kitakyushu.

Two community-level energy storage projects have also been installed at Kitakyushu, within the Kitakyushu Museum of Natural History and Human History. Both projects are designed for peak shifting, and indicate that the UltraBattery[®] is a suitable technology for the development of long-anticipated distributed storage throughout the grid. The first of the two projects is a 10 kW facility peak shifting application that uses 32 UltraBattery[®] cells (100 Ah,

6 V). The second is a 100 kW facility peak shifting application that uses 192 UltraBattery[®] cells (500 Ah, 2 V).

Storage systems based on UltraBattery[®] technology have now been deployed by Furukawa, East Penn, and Ecoult into a large number of grid and microgrid scaled power networks to manage variability, shift energy for grid stability, and enhance the utilization of renewable generation sources. The UltraBattery[®] is also advanced in the certification process of major automotive manufacturers. Generic products and solutions based on the UltraBattery[®] are being released progressively globally.

1.3 Publicly Available Research Considered

The following reports were considered in the preparation of this White Paper. Full details, including URLs where available, are provided in the References section at the end of this paper. The reports are shown here in reverse order of publication, and when interpreting some of the earlier results it should be remembered that UltraBattery[®] technology has advanced during the time covered by these reports. Figure 9 on page 24 provides a graphical summary of some such advancements.

Title	Author(s), Year	Summary
ALABC UltraBattery Hybrid Surpasses 100,000 Miles of Fleet Duty	ALABC, 2013	Document marking 100,000 miles of real-world fleet duty by a Honda Civic HEV with an UltraBattery [®] pack, achieved with minimal capacity loss
Development of UltraBattery	Furukawa, 2013	Paper in the <i>Furukawa Review</i> describing laboratory tests of UltraBattery [®] using profiles representing micro-HEV usage and stationary shifting and smoothing; charge–discharge voltages and the relation between longevity and efficiency and state of charge are explored in some depth
UltraBattery Energy Storage System for Hampton Wind Farm Field Trial: Summary of Activities and Outcomes	CSIRO, 2012	Comprehensive report on installing, commissioning, and operating a MW-scale UltraBattery [®] for smoothing wind farm output, with observations of battery performance; the voltage stability in a string of cells is particularly impressive
Development and Testing of an UltraBattery-Equipped Honda Civic Hybrid	INL, 2012	Comprehensive report on the development, testing, and fleet-vehicle operation of an UltraBattery [®] pack, with detailed comparative measurements of an NiMH battery pack and two UltraBattery [®] packs

Title	Author(s), Year	Summary
Life Cycle Testing and Evaluation of Energy Storage Devices	Ferreira, Baca, Hund, & Rose, 2012	Presentation on activities in the Sandia Energy Storage System Analysis Laboratory including high-rate and low-rate UltraBattery® longevity tests, using combined cycle profiles, which are relevant for utility and renewable energy applications
Further demonstration of the VRLA-type UltraBattery under medium-HEV duty and development of the flooded-type UltraBattery for micro-HEV applications	Furukawa, Takada, Monma, & Lam, 2010	Peer-reviewed journal paper on cell-level and string-level UltraBattery® testing, with emphasis on discharge voltage performance under several cycle-life test profiles, including high-temperature operation
UltraBattery Test Results for Utility Cycling Applications	Hund, Clark, & Baca, 2008	Conference paper from the Sandia team focusing on utility applications enabled by large-format UltraBattery® cells; provides detailed charge and discharge voltage behavior during pSoC cycling at different rates, from 1C to 4C
Development of UltraBattery: 3rd Report	Furukawa & CSIRO, 2008	Report showing extremely long cycle life, without recovery charging, of a 144 V UltraBattery® pack for micro- and medium HEV operation; includes direct comparison with conventional and idle-stop batteries as well as a simple wind energy-shifting profile

2 Value Proposition

The value proposition for the UltraBattery® is that it outperforms other lead-acid battery technologies in several important areas, including:

- + **Total lifetime energy throughput capacity for management of power variability** leading to lower lifetime cost per kWh
- + **Ability to operate continuously in a pSoC regime (i.e. operating in a band of charge that is neither totally full nor totally empty)** leading to viability of use models where energy is charged and discharged at significantly higher efficiency
- + **Charge acceptance (matched to discharge rate capability)** leading to quicker recharge
- + **Consistency of behavior of individual cells in long strings** leading to lower maintenance.

UltraBattery[®] technology can be used to continually manage energy intermittencies, smooth power and shift energy. As noted above, it combines the advantages of proven and dependable advanced lead-acid battery technology with the advantages of an asymmetric supercapacitor, enabling the optimal balance of an energy-storing lead-acid battery with the quick charge acceptance, power discharge and longevity of a supercapacitor. It is a competitive alternative to non-lead-acid battery technologies, which the UltraBattery[®] matches or exceeds for applications that manage power variability in second and minute timeframes as well as for energy-shifting applications of 1 to 4 hours.

The UltraBattery[®] cell has characteristics that make it resistant to many of the typical failure modes that make conventional lead-acid batteries unsuitable for certain applications, giving UltraBattery[®] technology a comparatively wider range of potential applications and a longer useful life. Standard valve-regulated lead-acid (VRLA) batteries form 'hard' lead sulfate deposits inside and on the surface of the porous negative plate when operated continuously in a pSoC regime, unless given frequent refresh overcharge cycles. However, the capacitor integrated into the UltraBattery[®] modifies the process associated with the formation and dissolution of sulfate crystals within the negative plate when discharging and charging, respectively. This enables the UltraBattery[®] cell to operate for long periods in the mid-charge band (the most efficient charge/discharge region for lead-acid cells) and, combined with the cycling endurance of the technology, results in an ability to process a much greater amount of energy (a significant multiple over standard lead-acid technology) in the device's usable lifetime.

This capability is fundamental to the technology's ability to meet typical grid requirements for smoothing the variable output of renewable generators and for shifting energy from periods of high production to periods of high demand.

The ability to work in constant pSoC is also crucial for HEV energy storage, where braking and acceleration occur in rapid repetition. UltraBattery[®] technology shows comparable performance (in miles per gallon terms) to that of a vehicle of the same model powered by nickel-metal hydride (NiMH) batteries, at significantly lower cost (ALABC, 2013). Furthermore, longevity, safety, efficiency, long uptimes, and full recyclability all point to potentially competitive triple-bottom-line advantages for UltraBattery[®] technology over chemistries whose safety and recyclability are yet to be demonstrated. The following table shows which publicly available test results support the UltraBattery[®] capabilities that comprise its value proposition.

Source of Test Data	High-Capacity Turnover/Longevity	Lower Lifetime Cost per kWh	High Efficiency	Fewer Refresh Cycles	Less Downtime	High Charge Acceptance	Lower Variability of Cell Voltage within Strings
ALABC, 2013	x	x					x
CSIRO, 2012							x
Ferreira et al., 2012	x	x		x	x		
Furukawa, 2013	x	x	x			x	
Furukawa & CSIRO, 2008	x	x					x
Furukawa et al., 2010							x
Hund et al., 2008	x	x				x	
INL, 2012	x	x	x	x	x		

3 Application Matrix Indicating Use Cases for UltraBattery® Technology

Each application of UltraBattery® technology has specific requirements that are met by different aspects of the value proposition. The following table maps applications to the publicly available test results that support the value proposition. For the most part, applications require either energy shifting at a low charging or discharging rate, or high-rate cycling at an intermediate or partial state of charge, with some requiring a mixture of these capabilities.

The table marks the applications that have been directly targeted by testing programs, using cycle profiles that represent typical operation. Some applications have not yet been explicitly represented in testing programs. This may be because earlier testing concentrated on applications that were considered more commercially relevant, or because some applications have only recently been envisaged and understood. New testing programs are underway to address a wider set of applications (see, for example, Ferguson, 2013).

While the columns headed ‘Power quality’ and ‘Residential energy management’ are empty, they have been included here because both applications are at an advanced stage of commercial development by Ecoult (with some projects installed and operational), since internal tests and extrapolations from other testing have shown the technology to be very well suited to these applications. Similarly, the ‘Railways’ column is also blank, indicating

that no specific testing has been performed on this application. However, on the basis of tests performed in other areas it is considered that UltraBattery® technology is well suited to supporting the very demanding requirements of railway energy management. A later section of this paper discusses railway requirements in greater detail.

Source of Test Data	Frequency Regulation	Smoothing and Ramp-Rate Control	Power Quality	Spinning Reserve	Residential Energy Management	Energy Shifting and Demand Management	Diesel Efficiencies	Multipurpose use in Datacenters and Commercial Buildings	Micro- and Medium HEVs	Railways
ALABC, 2013									x	
CSIRO, 2012		x								
Ferreira et al., 2012	x	x		x		x	x	x		
Furukawa, 2013		x				x		x	x	
Furukawa & CSIRO, 2008									x	
Furukawa et al., 2010									x	
Hund et al., 2008	x	x				x		x		
INL, 2012									x	

4 Tests Supporting the UltraBattery® Value Proposition

The publicly available test results that support the value proposition are here described in detail, so that they may be compared to the value proposition above and to the application requirements in a later section.

4.1 High-Capacity Turnover and Longevity

4.1.1 Defining Cycles and Capacity Turnover

The outstanding benefit of the UltraBattery® cell is its long life under cycling operations at pSoC. Quantifying this for disparate applications requires a definition of ‘capacity turnover’ that is separate from the concept of a ‘cycle’.

The common understanding of a cycle is a charging operation followed by a discharging operation, so that a new cycle is marked by a change in direction of power flow into or out of the cell, and not by a particular amount of energy stored and released. The full nameplate capacity of a battery is rarely or never used in a single cycle. Thus, although it is common to count cycles during a test, this is not a measure that can be compared between different tests that may use different application-specific cycles.

Capacity turnover measures the total energy throughput of a battery, up to the end of its life, as a multiple of the rated capacity of a battery. A comparison of battery life cycles becomes possible by comparing capacity turnovers. The UltraBattery[®] cell has a very large capacity turnover, exceeding by around four times (and in some applications by many more times) the capacity turnover of the best-performing VRLA batteries, as demonstrated in the tests described below.

Many tests have quantified the lifetime of the UltraBattery[®] for either vehicular or utility applications. It is useful to divide the tests into those that are high-rate and low-rate compared to the '1C' rate that would discharge the battery in 1 hour, and this terminology will be used in the following test summaries.

- + A high-rate test charges and discharges at the order of a 1C rate, and each cycle lasts for some minutes, therefore having a small depth of discharge (DoD) impact.
- + A low-rate test charges and discharges at a fraction of the 1C rate, and each cycle may last for some hours, therefore having a significant DoD impact.

High-rate tests usually represent 'balancing' applications for which responsive power delivery is required, as in HEVs, renewable energy smoothing, or regulation services. Low-rate tests usually represent 'energy-shifting' applications.

A battery is generally considered to have reached the end of its useful life when its available capacity is reduced to 70-80% of its nameplate capacity. It is quite possible, however, that such a battery may be repurposed to find continued use in another application, and offered at a lower price point than a new battery.

4.1.2 Longevity Tests by the Sandia National Laboratories

The Sandia National Laboratories have performed independent testing that has drawn substantial positive attention to UltraBattery[®] technology (Ferreira et al., 2012). The team at Sandia tested UltraBattery[®] cells made by both Furukawa and East Penn.

The test profile for high-rate, pSoC cycling represented a utility application with cycles of 5% DoD. An East Penn UltraBattery[®] ran for more than 20,000 cycles maintaining very close to 100% of its initial capacity, as shown in Figure 2. By comparison, the conventional VRLA battery fell below 80% of its initial capacity after approximately 2500 cycles.

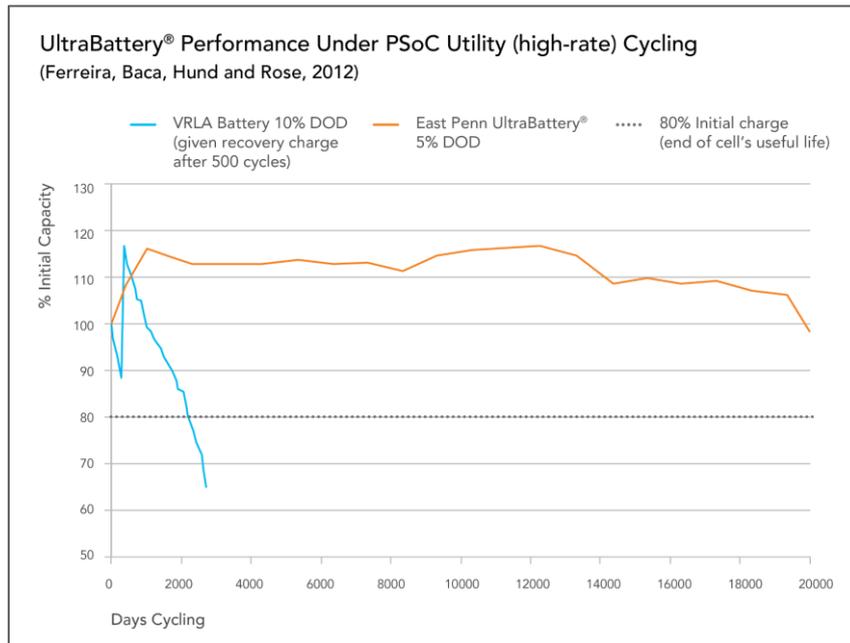


Figure 2: UltraBattery® performance under pSoC utility (high-rate) cycling (Ferreira et al., 2012)

Under the test profile for slow, low-rate, high-energy cycling, which is a PV hybrid test schedule, UltraBattery® cells manufactured by East Penn and Furukawa showed performance far exceeding that of traditional VRLA batteries, as shown in Figure 3. This performance was achieved even after 40 days without a recovery charge to 100% SoC (where a recovery charge is generally needed much more frequently to alleviate sulfation in conventional lead-acid cells).

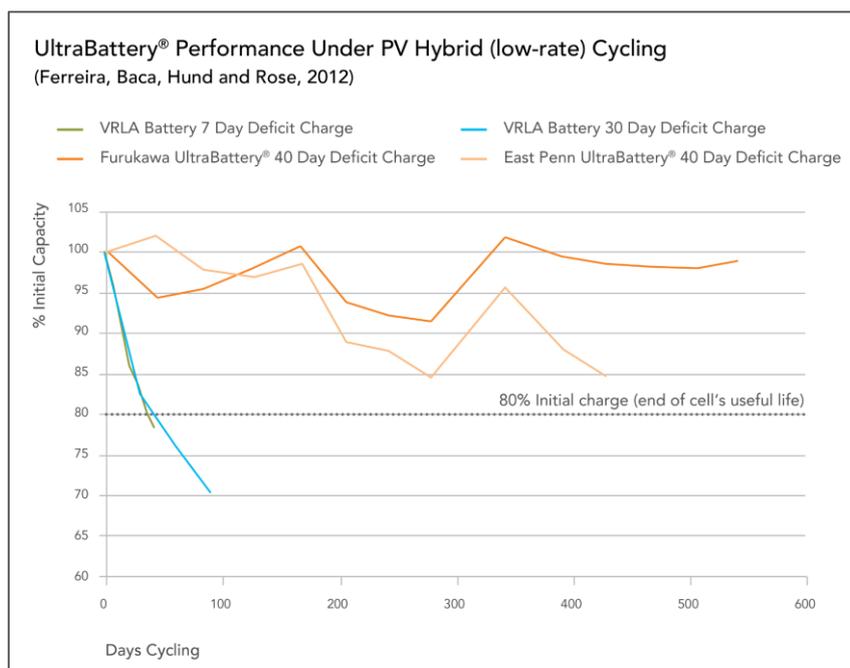


Figure 3: UltraBattery® performance under PV hybrid (low-rate) cycling (Ferreira et al., 2012)

These tests used large-format UltraBattery[®] units from East Penn and Furukawa designed for utility applications. Results of earlier high-rate pSoC cycling tests representative of regulation services performed by Hund et al. (2008) are shown in Figure 4. These used smaller-format Furukawa UltraBattery[®] cells and, this should be factored into consideration when comparing the performance but, together they show that the longevity of the cells was evident from the earliest publicly available tests across different applications and cell configurations.

Hund et al.'s 2008 tests were designed to expose the cells to groups of 100 or 1000 rapid charge–discharge cycles at a 1C, 2C, or 4C rate, covering a range of 10% DoD, separated by recovery charging at 1C for a capacity measurement, and then discharging at 1C to 50% SoC for the next group of rapid cycles.

As shown in Figure 4, the UltraBattery[®] cells lasted approximately 13 times longer (16,740 cycles) than the absorbed glass matt VRLA battery (1100 cycles). The UltraBattery[®] cells were also able to withstand more than 10 times the number of rapid cycles as compared to the VRLA battery (1000 vs 100) before a recovery charge.

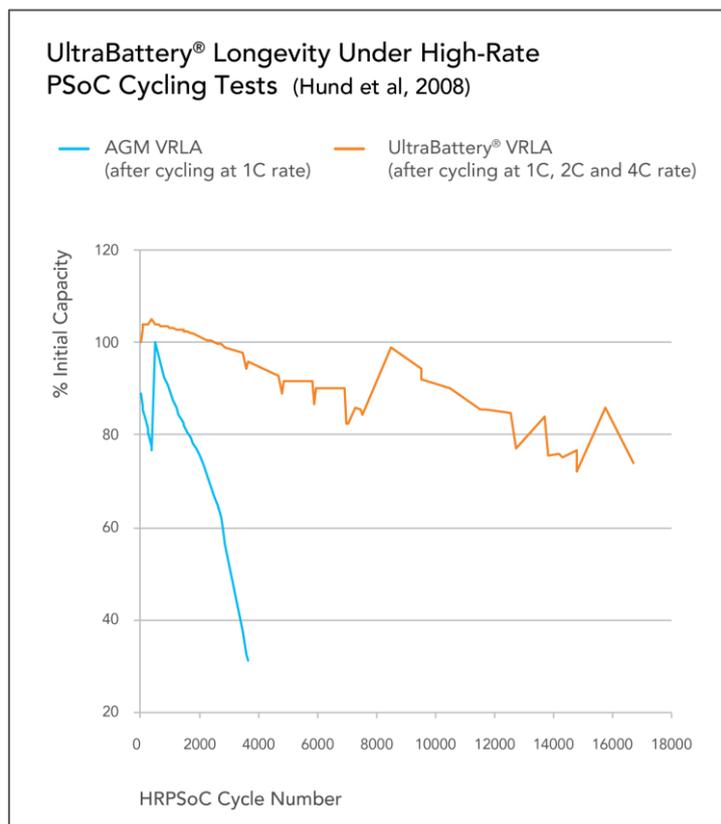


Figure 4: UltraBattery[®] longevity under earlier high-rate pSoC cycling tests (Hund et al., 2008)

The voltage and capacity chart for the UltraBattery[®] is shown in Figure 5, illustrating characteristics during charge and discharge before the first high-rate pSoC cycle (green trace), after 500 cycles (blue trace), and after 16,740 high-rate pSoC cycles (red trace).

At an initial capacity of 7.8 Ah, the UltraBattery[®] exceeded the manufacturer’s specified capacity of 6.67 Ah (117% of rated capacity). After 500 cycles, the capacity *increased* to 8.1 Ah (121% of rated capacity). Such an increase in capacity, while unusual in lead-acid cells, is typically seen in UltraBattery[®] cells at the onset of testing and use (in more recent testing, following improvements to the cells, this increase is far more marked and long-lasting). The capacity after 16,740 cycles was 5.8 Ah. This is 87% of rated capacity, so the battery was still considered to be well within its useful life at the conclusion of testing.

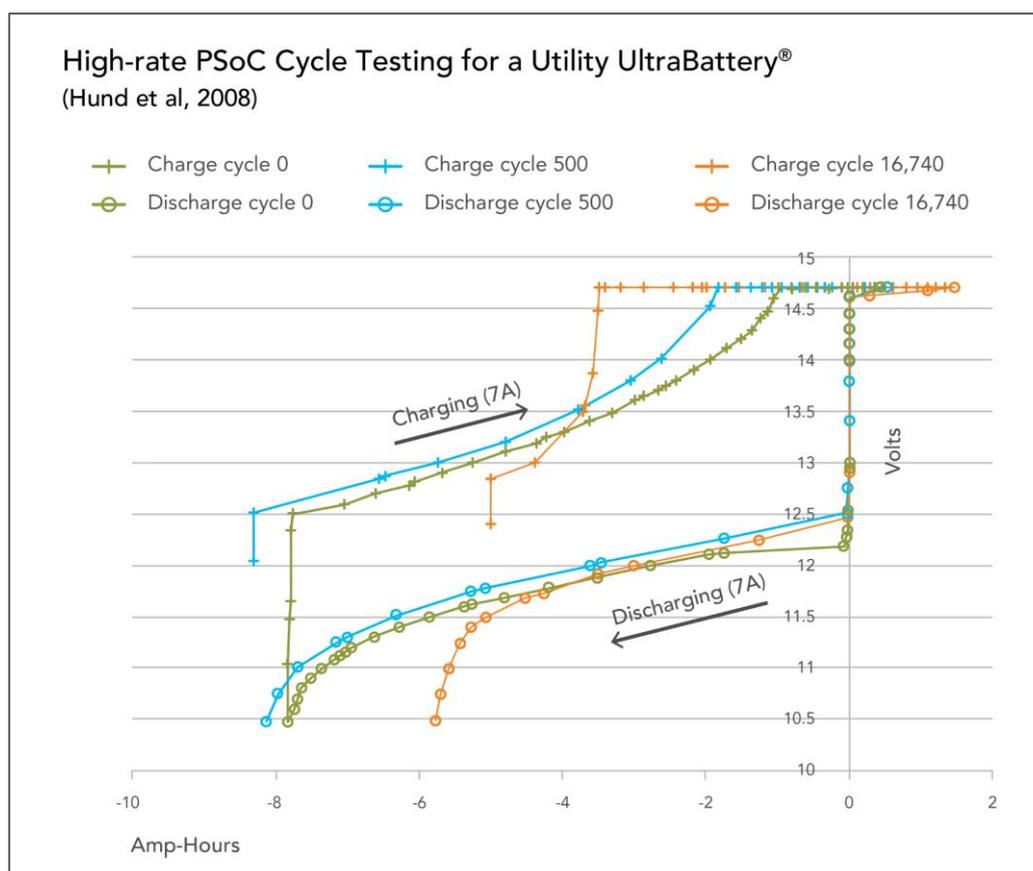


Figure 5: High-rate pSoC cycle testing for a utility UltraBattery[®]. The lower three traces show discharging; the upper three show charging. Note that the charge and discharge are 'looped'. The green loop plots the measurements on the first charge–discharge cycle. The blue loop represents the 500th charge–discharge cycle and shows an increased capacity on the starting cycle. The red loop represents the 16,740th charge–discharge cycle, and shows that some reduction in capacity has taken place (Hund et al., 2008).

4.1.3 Longevity Tests by the Furukawa Battery Company

The Furukawa Battery Company has manufactured UltraBattery[®] cells for both micro-HEV and utility applications, and has pursued a thorough testing program in parallel (Furukawa, 2013). Batteries in micro-HEVs are used differently from standard car batteries in the following three main respects.

- + They should withstand deeper discharge so they can power the car’s electrical systems when the engine stops idling.

- + They should withstand a larger number of deep-current discharges to start the motor again each time it stops idling.
- + They should operate at about 90% SoC so there is some headroom to accept current from regenerative braking.

A cycling test that exhibited these characteristics was applied to a Furukawa UltraBattery[®] and to a conventional lead-acid battery designed for micro-HEV use (Furukawa, 2013). This test used a 5% DoD and was performed at three different states of charge. As the SoC increased from 70% to 90%, the capacity turnover increased from 530 to 720, as shown in Figure 6. The UltraBattery[®] unit had approximately 1.8 times as much capacity turnover as the conventional battery under the condition of 70% SoC. The conventional battery was not tested at 80% or 90% SoC.

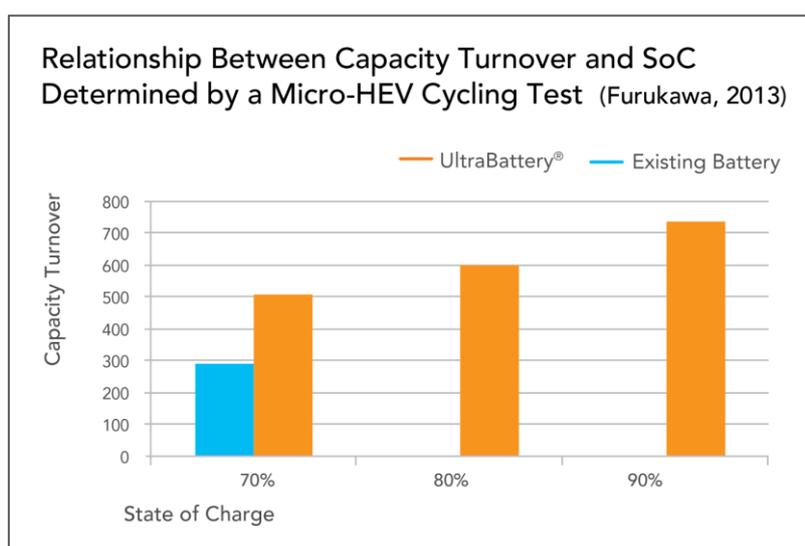


Figure 6: The relationship between capacity turnover and SoC determined by a micro-HEV cycling test (Furukawa, 2013)

After testing, the batteries were dismantled for analysis. The conventional battery showed significantly sulfated negative active materials, whereas the UltraBattery[®] cells showed little negative electrode sulfation. This is one of the reasons why the UltraBattery[®] exhibits good lifetime characteristics, as negative plate degradation is a significant failure mode in conventional VRLA batteries used for pSoC applications.

Furukawa also performed tests designed to show that UltraBattery[®] technology was suited to utility applications. A Furukawa UltraBattery[®] unit was subjected to a high-rate pSoC cycle test, following a very similar pattern to the Sandia National Laboratories test described above. After adjusting the SoC to 50% at 1C charge current, there was a group of 1000 charge–discharge cycles at a 1C rate for 6 minutes in each direction, covering therefore a 10% DoD, with a break for 5 minutes between each direction. Groups were repeated to end of life, separated by a 1C charge and capacity test.

Compared at the point where the capacity ratios dropped to 80%, the life of the UltraBattery[®] cell is twice as long as that of the existing lead storage battery, as can be seen in Figure 7.

This doubling of life expectancy is a significant performance advantage (although the Furukawa cell has shown significantly better performance in other tests, including those noted below which show the cell still operating successfully after an extraordinary 1.4 million cycles.)

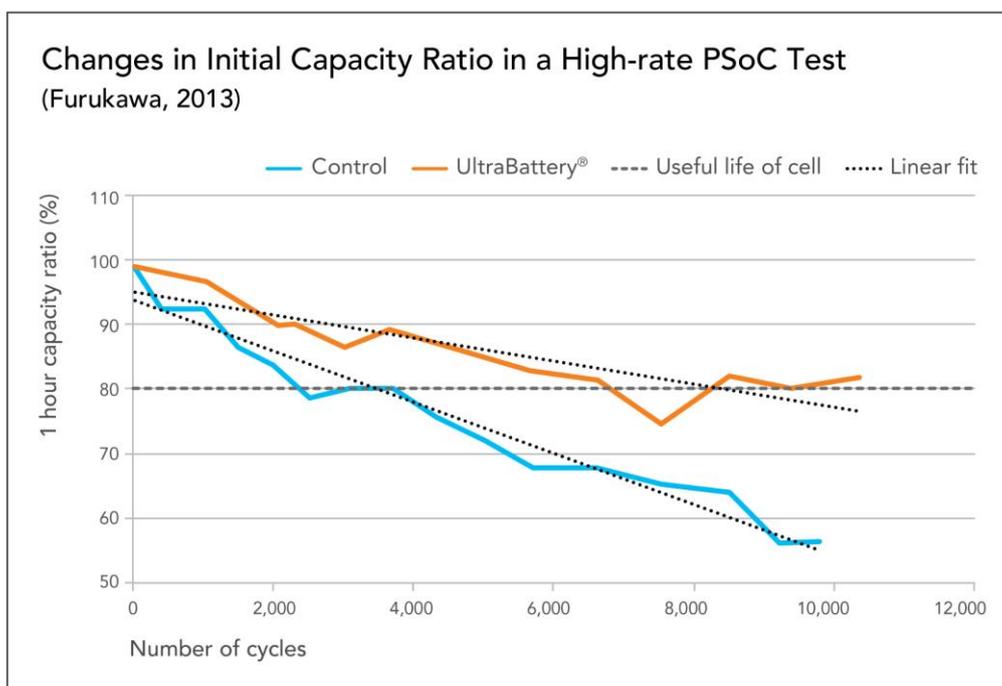


Figure 7: Changes in initial capacity ratio in a high-rate pSoC test (Furukawa, 2013)

4.1.4 Medium-HEV Field Testing by CSIRO and the Furukawa Battery Company

The suitability of the UltraBattery® cell for vehicular applications has been demonstrated by two long-distance driving tests as well as by laboratory cycling tests.

The first driving test was carried out on a test circuit in January 2008. A 144 V module using prototype Furukawa UltraBattery® cells was installed in a Honda Insight HEV, and a drive of 100,000 miles (160,000 km) was achieved without recovery charging. Remarkably, the UltraBattery® cells remained in good condition after the drive (Furukawa & CSIRO, 2008).

Of particular significance is that this field driving test demonstrated no difference between the driving performance of the HEV using the UltraBattery® pack and that of the HEV using the NiMH battery pack. It has also been shown that the cost of the UltraBattery® cells was dramatically less than that of the NiMH cells, and that fuel efficiency and carbon dioxide emissions were almost the same between the two cell chemistries.

To follow up and further quantify the road test results, a laboratory cycle-life test was conducted for the 2 V cell flooded type Furukawa UltraBattery® based on the power-assisting EUCAR profile (Furukawa & CSIRO, 2008; Furukawa et al., 2010). The test was started at 60% SoC, and no recovering charging was done. The life of the UltraBattery® cell, however, was more than 40,000 cycles, representing a cycle life more than 10 times longer than that

of a conventional lead-acid battery, and more than four times longer than that of a lead-acid battery designed for idling-stop-start (ISS) vehicles. This comparison is shown in Figure 8.

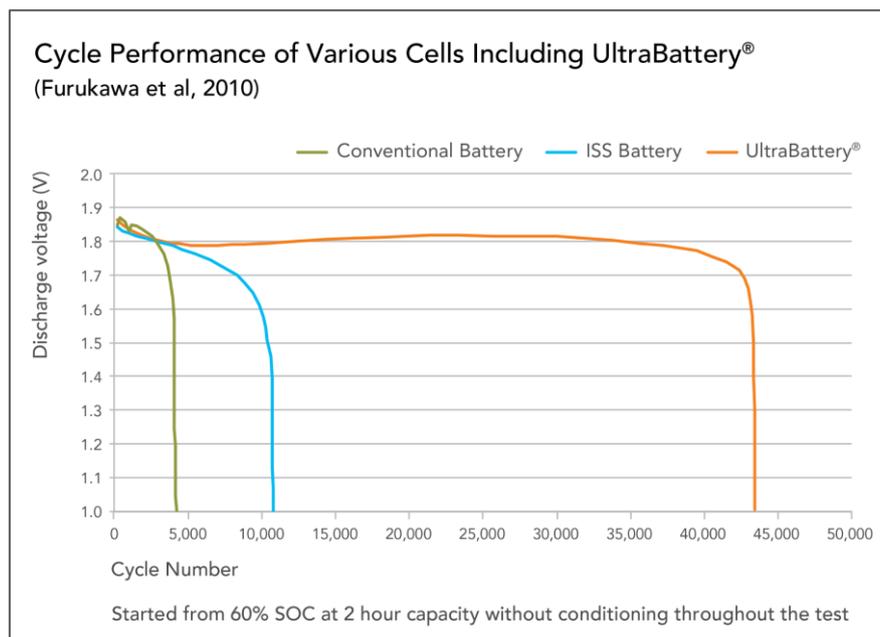


Figure 8: Cycle performance of a conventional battery, an ISS battery, and an UltraBattery® under the power-assisting EUCAR profile (Furukawa et al., 2010)

Another laboratory life-cycle test was performed with a 12 V unit (six 2 V UltraBattery® cells packaged in the manner of commonly observed 12 V industrial lead-acid batteries) with five-hour capacity of 8.5 Ah connected in series to make a 144 V battery pack (Furukawa et al., 2010). The battery pack was then cycled under a simulated, medium-HEV profile. This profile comprised 10 cycles, with each cycle comprising several discharge and charge steps of different rates and durations.

The average time of one cycle in the profile was 33 s, and the discharge–charge window was approximately 0.35% of the nominal five-hour capacity. From a fully charged state, the UltraBattery® pack was discharged at five-hour rate to 60% SoC and then subjected repetitively to the above profile for five days, followed by two days resting at open circuit. This simulates a week of car use for commuting. This ‘test week’ was then repeated, with no conditioning or equalization charge.

At the time of publication of the report (Furukawa et al., 2010), after two years of testing the UltraBattery® pack had already passed 1,400,000 cycles, which is seven times greater than the target value of 200,000 cycles. The capacity turnover corresponding to this number of cycles is 5000 (that is, the full capacity of the cells has been turned over 5000 times during the test). No major decrease in the pack voltage was observed, despite no conditioning or equalization charge being performed during the test.

4.1.5 Medium-HEV Field Testing by the Idaho National Laboratory

The second driving test used a fleet vehicle experiencing real road conditions. The Idaho National Laboratory (INL, 2012) undertook this test within the UltraBattery® Retrofit Project

DP1.8 and Carbon Enriched Project C3, performed by ECOtality North America and funded by the US Department of Energy and ALABC. These tests were established to demonstrate the suitability of advanced lead-acid battery technology in HEVs.

In preparation for this driving test, a Furukawa UltraBattery[®] pack operated trouble free for 60,000 simulated miles (96,000 km) under Simulated Honda Civic HEV Profile (SHCHEVP) at 30°C (86°F), with minimal drop in performance. A vehicle-sized pack of East Penn UltraBattery[®] packs also delivered 60,000 miles under SHCHEVP at 30°C. The simulation allowed tests to be performed in laboratory conditions but was calibrated against cells housed in actual HEVs, and the lab and field tests were shown to produce virtually identical results.

The UltraBattery[®] modules showed remarkably low rates of voltage divergence: all cells remained very close to each other in performance and capacity throughout their lifetimes. Logging of individual 12 V modules showed that less than one-quarter of a volt separated all modules at the end of more than 45,000 miles (72,000 km) of simulated driving.

These results are very promising and, combined with the results for the individual module cycling, they suggest that a single UltraBattery[®] pack may be capable of lasting the design life of a modern HEV (160,000 miles or 260,000 km). To compare UltraBattery[®] performance against other advanced lead-acid cell designs, a vehicle-sized pack of high-carbon ALABC lead-acid modules (not UltraBattery[®] cells) was operated under SHCHEVP, and it failed after 27,000 simulated miles (43,500 km). A vehicle-sized, high-carbon, lead-acid battery from Exide was also cycled under SHCHEVP, but it failed after 12,500 simulated miles (20,000 km) (INL, 2012).

In October 2011, the converted HEV using an East Penn UltraBattery[®] pack was put into ECOtality's fleet of test vehicles in Phoenix, Arizona, and it is currently accumulating approximately 5000 miles (8000 km) per month. At the end of August 2012, the vehicle had accumulated more than 60,000 miles and had experienced a wide range of driving conditions and demanding ambient temperatures. The battery capacity was measured at 7.54 Ah (at a C1 rate) after 51,000 miles (82,000 km) of driving, which is an insignificant capacity loss against the average capacity of the new modules, which is 7.55 Ah.

By June 2013, the converted HEV had recorded more than 100,000 miles (160,000 km) of courier duty in the local area of Phoenix, Arizona. The HEV demonstrator achieved the benchmark in the varying temperatures and elevations of the Phoenix area in just under two years of operation with no significant loss in battery capacity.

4.2 Chronology of All Longevity Tests Discussed in this Paper

UltraBattery[®] technology has been continuously developed since its invention, with further innovations from CSIRO and the technology's two manufacturers applied to each new version of the product. This means that test results from different laboratories at different times may not be directly comparable. Because longevity tests have been the most frequently performed of all UltraBattery[®] characterizations, the table below compares the longevity results from several sources of test data, in order of date of publication of the results.

A significant increase in performance over traditional VRLA technology is evident in all the test results. However, due to the very wide range of test conditions (such as cycling profile, temperature, cell configuration and refresh charging regime), these results also are not necessarily directly comparable.

Developments in UltraBattery® technology over time are not necessarily discernible within the range of results shown in the table below. However, if the most recent internal testing is included then the trend toward greater energy throughput in the lifetime of the UltraBattery® cell is very clear (see Figure 9, below).

Source	Year	Manufacturer	Cycling Depth	Rate	Lifetime*	Conventional Lead-Acid	Ratio	Notes
Hund et al., 2008	2008	Furukawa	10%	High	16,740 c	1,100 c	15.2	
Furukawa et al., 2010	2010	Furukawa 2V	n/a	Low	43,000 c	4,000 c	10.8	
Furukawa et al., 2010	2010	Furukawa flooded cell	n/a	High	75,000 c	15,000 c	5.0	ISS cycle
Furukawa et al., 2010	2010	Furukawa flooded cell	n/a	High	8,000 c	2,000 c	4.0	
Ferreira et al., 2012	2012	East Penn	5%	High	>20,000 c	2,500 c	8.0	
Ferreira et al., 2012	2012	Furukawa	5%	High	5,000 c	2,500 c	2.0	High temp.
Ferreira et al., 2012	2012	East Penn	n/a	Low	> 430 d	40 d	10.8	
Ferreira et al., 2012	2012	Furukawa	n/a	Low	> 550 d	40 d	13.8	
INL, 2012	2012	Furukawa	10%	HEV	> 60,000 mi	12,500–27,000 mi	2.2–4.8	
INL, 2012	2012	East Penn	10%	HEV	> 60,000 mi	12,500–27,000 mi	2.2–4.8	

INL, 2012	2012	East Penn	10%	HEV	167,000 mi	40,391 mi	4.1
Furukawa, 2013	2013	Furukawa	5%	Low	720 t	290 t	2.5
Furukawa, 2013	2013	Furukawa	10%	High	8,800 c	3,700 c	2.4

* Measured in days (d), cycles (c), capacity turnover (t), or HEV miles (mi)

The trace marked Sandia UB12 in Figure 9 shows UltraBattery® results from the Sandia National Laboratories from 2008. These are very similar to many pre-2013 results for UltraBattery® cells. Note that Li-ion testing performed concurrently showed UltraBattery® technology to be on par with the Li-ion tests at the time. The most recent testing performed internally in 2013 (by Ecoult and East Penn Manufacturing) is indicated by the top three traces in Figure 9, and illustrates the significant improvements made to UltraBattery® technology in the past few years.

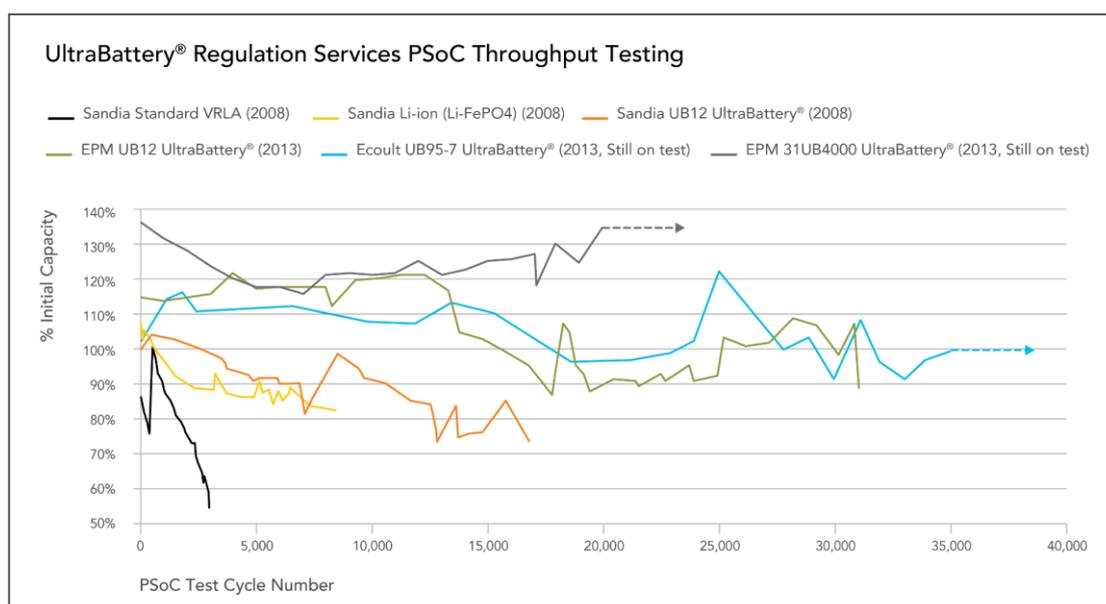


Figure 9: Energy throughput testing showing Sandia National Laboratories results from 2008 (lower three traces) for VRLA, UltraBattery® (UB12) and Li-Ion test results. The Sandia results are compared against internal testing carried out by Ecoult and East Penn Manufacturing (top three traces) performed in mid-2013. There is a clear trend toward increasing throughput as the UltraBattery® cells are improved over time.

4.3 Lower Lifetime Cost per kWh Delivered

As a consequence of high-capacity turnover and longevity, UltraBattery® cells need less frequent replacements than VRLA batteries in active power applications, and can have a much greater energy throughput during their lifetimes. Therefore the cost relative to the throughput, measured per kWh delivered, is significantly lower.

The actual cost per kWh delivered depends on the cycling pattern required by the application. For example, using estimated cycling requirements for frequency control ancillary services (FCAS) in Australia (in costings done for the Tasmanian market), the UltraBattery[®] was the only technology that would deliver a profit in this application (James & Hayward, 2012). (Note that in that report the UltraBattery[®] is referred to as an ‘advanced lead-acid battery’. However, this is not strictly accurate since this term is usually used to describe a type of storage device with no supercapacitive chemistry and with different characteristics from the UltraBattery[®].)

An end-to-end calculation of the fuel efficiency of a Honda Civic HEV using an UltraBattery[®] pack (ALABC, 2013) shows that this car has achieved comparable mpg performance with that of the same model powered by NiMH batteries but at a significantly lower cost.

4.4 High Efficiency

The UltraBattery[®] cell achieves typical DC–DC efficiency of 93–95% when performing variability management applications such as regulation services or renewable ramp rate smoothing at 1C peak power in a pSoC regime.

The UltraBattery[®] also achieves typical DC–DC efficiency of between 86% and 95% (rate dependent) when performing energy-shifting applications in pSoC. This high efficiency compares favorably with the typical efficiency of less than 70% when standard VRLA batteries are applied to energy shifting using the typical top-of-charge regime.

Efficiency testing was undertaken at the Furukawa Battery Company for 2 V UltraBattery[®] cells with capacity 1000 Ah at a 10-hour rate, intended for stationary applications (Furukawa, 2013). The SoC was adjusted in increments of 10%, and 30 charge–discharge cycles were performed at rates of between 0.1C and 0.6C, followed by a recovery charge.

During cycling the quantity of charge–discharge electricity was equivalent to 10% of the rated capacity, ensuring that the efficiency measurement was not dominated by the SoC adjustment and recovery charging, thereby providing acceptable accuracy. The stationary UltraBattery[®] showed Wh efficiencies of 91–94.5% for 0.1C charge–discharge cycling, and of 83–87% for 0.45C–0.6C charge–discharge cycling, for SoC in the range of 30–90% as shown in Figure 10.

Thus, the UltraBattery[®] demonstrated high Wh efficiencies not only for low charge–discharge currents but also for high charge–discharge currents.

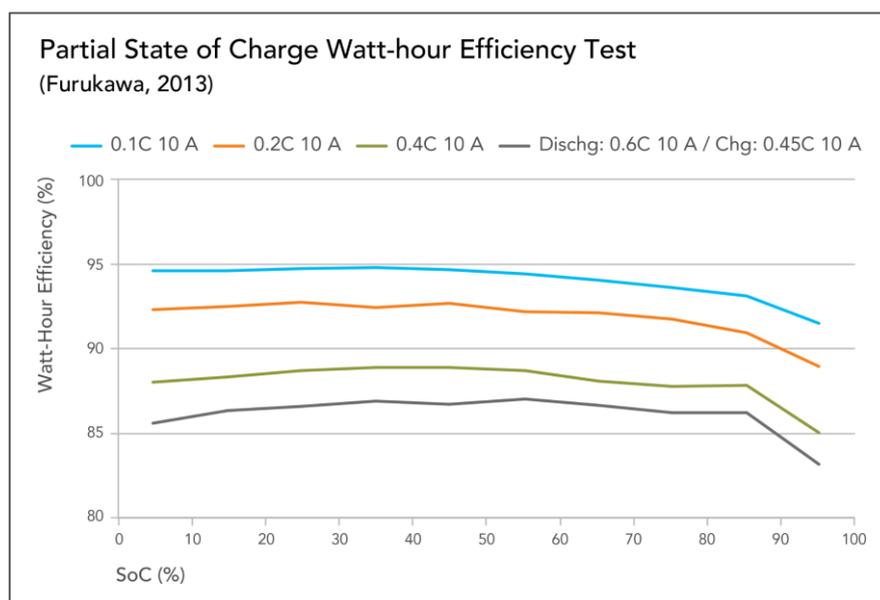


Figure 10: Results of efficiency testing undertaken at the Furukawa Battery Company (Furukawa, 2013)

Fuel efficiency is a measure of interest for HEV applications. For example, the Honda Insight HEV with an UltraBattery[®] pack, used for fleet duties, delivers an average of 44 mpg (5.3 L/100 km) in fuel economy when driven in mild temperatures and on reasonably flat terrain. This drops to approximately 35 mpg (6.7 L/100 km) when the temperature increases and the terrain become hillier (INL, 2012).

This measure does not relate directly to the electrical efficiency of the battery pack, because it is also affected by many additional factors including the battery capacity and its ability to accept regenerative braking power. An adequate compromise between vehicle acceleration and charging efficiency during regenerative braking is provided with an SoC window of 53–63%.

Operating at warm temperatures (30°C, or 86°F), the number of simulated vehicle miles covered before a simulated engine recharge is required is 142 miles (229 km) (INL, 2012).

4.5 Fewer Refresh Charges

Lead-acid batteries (like other battery technologies) periodically require a refresh charge, typically at a 1C rate, followed by a lengthy period of lower-rate charging at a ‘float’ voltage so that all cells reach 100% SoC. This helps to restore the physical state of the electrodes and allows the individual battery cells to attain consistent voltages and SoC, when otherwise they might diverge during an extended period of cycling. A refresh cycle concludes when the battery is returned to the SoC required by the application it is serving.

During a refresh cycle, therefore, the battery is not serving the application and so it is desirable to minimize this downtime. The UltraBattery[®] requires less frequent refresh cycles than a conventional VRLA battery, and this increases the time it spends on active duty.

Under PV hybrid cycling (Ferreira et al., 2012), which is a low-rate, high-energy schedule, the East Penn UltraBattery[®] after 40 days without a refresh charge showed performance far

exceeding that of traditional VRLA batteries that had gone only seven days without a refresh charge, as shown in Figure 11.

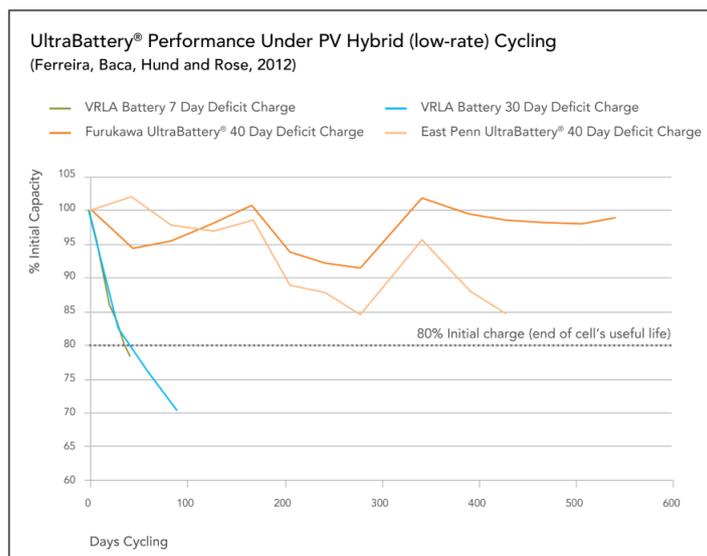


Figure 11: UltraBattery® performance under PV hybrid cycling (adapted from Ferreira et al., 2012)

One of the most impressive demonstrations of UltraBattery® longevity was during a test of a 144 V UltraBattery® module for HEV use, created by connecting 12 prototype Furukawa UltraBattery® cells in series. A life test was conducted of these modules in pSoC conditions simulating hybrid functions such as motor assistance at start-up and during acceleration, brake regeneration, and idle stop (Furukawa & CSIRO, 2008). The test was still underway even after 1,400,000 cycles had been achieved, with no refresh cycles at all. The capacity turnover of the UltraBattery® module exceeded 5000, which is an extraordinary value for a life test conducted on a lead-acid battery (or indeed on any battery) in pSoC conditions without recovery cycles.

UltraBattery® technology has also been tested with low rates of recovery charging in stationary applications. The cells consistently show capacity ratios equal to or exceeding 100% despite having been cycled many times and only receiving infrequent recovery cycles. For example, in a Furukawa Battery Company test under pSoC (Furukawa, 2013), a regime was devised whereby the cells were consistently cycled (charged and discharged) between 30% and 60%, with a recovery charge to float conditions being delivered only once per month. The cells tested were confirmed to have superior recovery charge characteristics compared with traditional VRLA batteries and, whereas the traditional VRLA cells declined steadily in capacity throughout testing (despite receiving recovery charges), the UltraBattery® cells *increased* in capacity from 100% and were above 103% capacity and still rising after several months of testing (the tests continued after the 2013 report was published).

Internal testing is continuing in order to determine the most efficient recovery charge interval for UltraBattery® technology to balance system uptime and cell longevity.

4.6 Less Downtime

This aspect of the value proposition is a consequence of requiring fewer refresh cycles. If refreshed for several hours once every 60 days, for example, the UltraBattery® can have downtime of less than 1% and thus be available for use more than 99% of the time. As discussed above, UltraBattery® cells have been shown in numerous tests to require very infrequent refresh charging (see, for example, Furukawa, 2013; and Ferreira et al., 2012).

4.7 High Charge Acceptance

When used in a pSoC regime performing variability management applications, such as regulation services or renewable ramp rate smoothing, UltraBattery® technology has exceptional charge acceptance capability. The actual charge acceptance rate is dependent on the particular UltraBattery® cell, but it is typically a multiple improvement on the charge acceptance capability of conventional VRLA batteries used in a typical top-of-charge cycling regime.

Charge acceptance depends on the voltage rise experienced during charging. If the voltage rises to the cell's or the pack's upper limit then no further charge can be accepted. During discharge no significant gap was observed between the UltraBattery® and a control battery (Furukawa, 2013). However, with respect to high-rate pSoC charging, the voltage of the UltraBattery® scarcely reached the charge terminal voltage, as shown in Figure 12, whereas the voltage of the conventional lead-acid battery frequently peaked to the charge terminal voltage. This indicates that the charge voltage of the UltraBattery® is very stable compared with traditional VRLA technology, signifying low internal impedance and good charge acceptance.

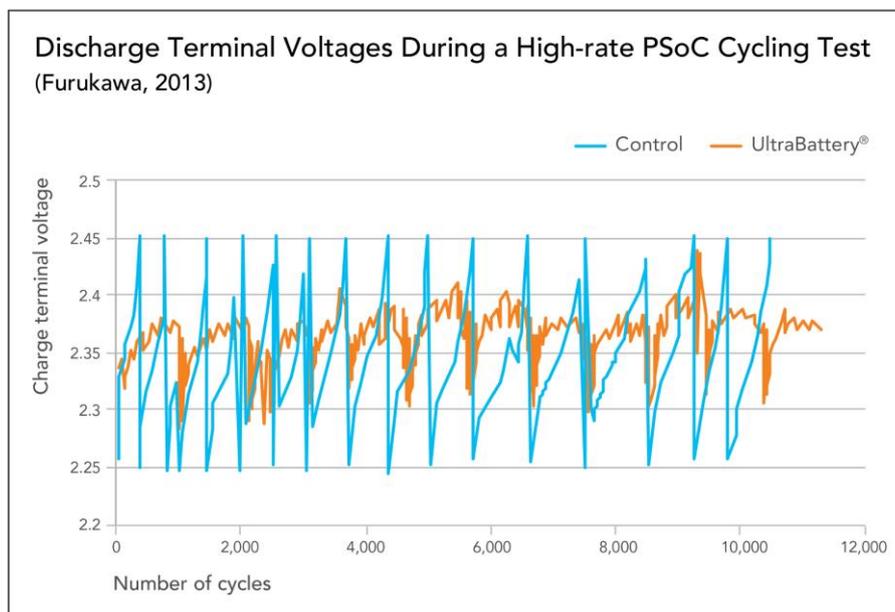


Figure 12: Discharge terminal voltages during a high-rate pSoC cycling test (Furukawa, 2013)

The sensitivity of charge and discharge voltages to rates was conducted on a Furukawa UltraBattery® at 50% SoC (Furukawa, 2013). Charge–discharge was conducted for 30 seconds at each rate and a break was given for 10 minutes after each charge–discharge.

4.8 Lower Variability of Cell Voltage Within Strings

Battery packs are made from ‘strings’ of individual cells connected in series so that their voltage sums to a high enough level for efficient power conversion. For example, a 144 V battery pack is typical for a medium HEV, whereas grid applications prefer voltages in the order of 500 V or more. Strings may be connected in parallel to increase the power capability of the battery pack.

During charging and discharging there is no control over individual battery cells in a series string, so their voltages and SoC may diverge over a period of cycling. This results in different rates of aging and some cells will fail earlier than they ideally would, disabling the whole string.

The presence of both the supercapacitor and battery chemistry in a single electrolyte in the UltraBattery[®] helps the cells in a string to equalize their voltages and SoC during extended periods of cycling. This was convincingly demonstrated when a direct comparison of the performance of four lead-acid battery technologies, including the UltraBattery[®], was undertaken as part of a trial of renewable energy smoothing at Hampton Wind Farm in Australia (CSIRO, 2012).

The relative stability of cell voltages within a string is illustrated in Figure 13, which shows cell voltage variability in strings during a 10-month period of intensive operation. In numerical terms, over these 10 months the variability of UltraBattery[®] cell voltages (measured as the standard deviation of the graphed daily variation) increased by only 32%, while the variability of cell voltages of other lead-acid technologies increased between 140% and 251%.

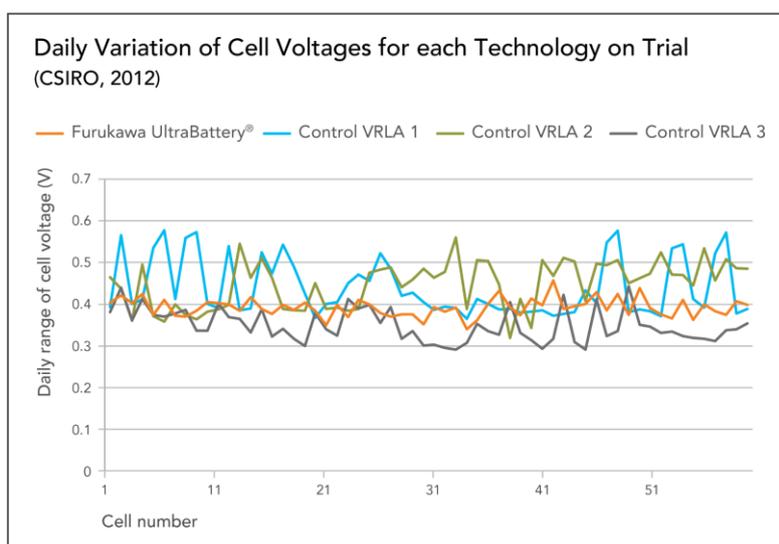


Figure 13: Comparison of daily variation of cell voltages over four lead-acid battery technologies after 10 months of operation at a wind farm, in which the UltraBattery[®] (thick blue line) shows much greater stability (CSIRO, 2012)

Cell voltage stability within a string was also demonstrated for an UltraBattery[®] module developed for HEV use (Furukawa & CSIRO, 2008; Furukawa et al., 2010). Figure 14 shows that the voltage deviations between individual batteries in a conventional VRLA string were rapidly enlarged during the initial 200,000 cycles, and this pack had to be removed from the test. On the other hand, it is clear that voltage deviations between the individual

UltraBattery® cells were small even after the UltraBattery® pack had undergone 1,400,000 cycles. The reason for the suppression of voltage deviations in the UltraBattery® string is hypothesized to be the greater charge acceptance of the capacitor components in these batteries, although this is an area where research continues. Maximizing the suppression of voltage deviations is fundamental to longevity and hence to low lifetime costs.

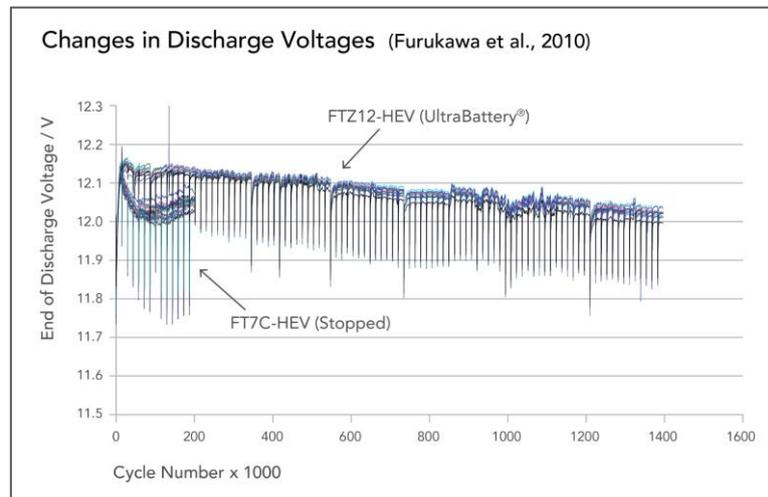


Figure 14: Changes in discharge voltages in individual batteries in 144 V strings of conventional VRLA and UltraBattery® cells under simulated medium-HEV cycling (Furukawa et al., 2010)

Observations of a Honda Civic HEV retrofitted with an UltraBattery® pack and subjected to fleet usage also demonstrated cell voltage stability (ALABC, 2013). After reaching 50,000 miles, the battery pack of this car showed no performance degradation and the individual battery voltages of the pack actually converged as they aged. This indicates not only that long lifetimes are possible, but also that UltraBattery® technology may operate with a battery monitoring system considerably lower in both complexity and expense than the systems required by other battery technologies.

4.9 Safety

Lead-acid batteries have been used for well over a century, and this familiarity has created a good understanding of safe practices. The UltraBattery® cell has the same safety requirements and benefits as any lead-acid battery. Its electrodes and electrolyte are non-flammable and have fire-retarding tendencies.

UltraBattery® technology is generally of the VRLA or ‘non-spillable’ design, which has achieved certification by IATA and DOT as being non-hazardous for transportation. Such is the safety record of VRLA batteries that, according to UN2800 *Batteries, wet, non-spillable, electric storage*, unless in a damaged condition, they are not subject to the US Hazardous Materials Regulations, meaning that there are no restrictions on their shipment by air or other transportation channels.

The electrolyte (aqueous sulfuric acid) is well managed through the life cycle of lead-acid battery manufacturing, transport, use, and disposal. Most lead-acid manufacturing plants recycle all elements of lead-acid cells and batteries, including the electrolyte. UltraBattery® manufacturer East Penn Manufacturing approaches 100% recycling rates for lead-acid

products processed at its own recycling plant at its manufacturing facility at Lyon Station, Pennsylvania.

Any battery should be ventilated so that hydrogen generated by overcharging is able to escape. Because lead-acid batteries are already widely used in stationary and vehicular applications, there are standard installation practices in place to ensure that these requirements are met. While lead is an environmental contaminant that must be regulated, it has generally been through exposure to paint products and to factory and vehicle exhaust fumes that adverse effects in humans and animals to lead have occurred.

The very high rates of recycling of lead-acid batteries prevents any significant release of lead into the environment from lead-acid battery production and use. While the lead-acid battery supply chain consumes more than 80% of the lead used in the USA, it is responsible for less than 1% of the country's lead emissions.

4.10 Recyclability

Lead-acid batteries of all kinds are virtually 100% recyclable, including the battery's plastic, steel, acid, and lead components. Lead-acid batteries have very high recycling rates around the world and are the most fully recycled product in many countries, including the USA. The US Environmental Protection Agency (EPA) states that in the USA, 96% of all lead-acid batteries are recycled, and that a typical lead-acid battery contains 60–80% recycled lead and plastic (epa.gov/osw/conservematerials/battery.htm).

In Australia, the Australian Bureau of Statistics states that 60% of all lead used in Australia is recycled, and that 93% of all motor vehicle batteries are recycled (Louey, 2010).

The European Union document 'Questions and Answers on the Batteries Directive (2006/66/Ec)' states that the collection of industrial and automotive lead-acid batteries in the EU is close to 100%.

As the energy storage industry develops and fulfills multiple applications in the electricity sector, well-managed recycling programs can be anticipated, following the precedent of the motor industry: for lead-acid technology, recycling rates of essentially 100% are not unexpected.

UltraBattery[®] recycling rates are expected to be higher than the standard recovery rates for lead-acid batteries for two reasons. Firstly, the units are shipped and used in containerized groups to known locations, whereas car-starter batteries are distributed individually and their location is not tracked. Secondly, the license holders for UltraBattery[®] manufacturing have strong existing recycling records.

For instance, UltraBattery[®] manufacturer East Penn Manufacturing has developed one of the world's most advanced lead-acid battery recycling facilities, which processes approximately 30,000 used lead-acid batteries per day. East Penn documentation (www.ultrabattery.com/recycling) describes the various stages in recovery, beginning with the batteries being collected, dismantled and separated. The lead is then smelted, then refined. Sulfur fumes created during the lead smelting process are trapped and processed into a liquid fertilizer solution. The plastic jars, cases and covers are cleaned and ground into polypropylene pellets that are then molded into new cases and parts at the company's onsite injection molding facility. East Penn recycles more than 11.8 million pounds (5.4 million

kilograms) of plastic per year. Finally, the company's acid reclamation plant recycles approximately 6 million gallons (23 million liters) of acid per year.

The motivations for recycling are both environmental and economic. Production of secondary lead uses approximately one-third of the energy required to produce lead from lead ore, so recycling provides large financial and energy savings as well as reducing requirements for mining and smelting.

4.11 Separate Low-Rate and High-Rate Energy Capacities

Peukert's law explains how the capacity of a lead-acid battery changes according to the rate at which it is discharged. Typically, when lead-acid batteries are discharged quickly, only a small portion of the total available stored energy can be accessed. Fast discharging affects the reacting chemicals, which are at the interface between the electrodes and the electrolyte, and uses only the surface of the plate. Slower discharging allows for the diffusion of the reaction deeper into the plates, using more of the available active material.

By careful sizing of the lead-acid cell and its parallel-connected supercapacitor, one application can be low-rate in relative terms, drawing on the deeper active material in the plates, while the other can be high-rate, operating only at the surface of the plates. Applied this way, UltraBattery[®] technology may serve multiple applications simultaneously and almost independently (Wood, 2013).

5 Proposed Applications of UltraBattery[®] Technology

The flexibility of energy storage, particularly with respect to responsive battery technology and advanced power electronics, has excited the power and automotive industries because of the range of benefits that may be obtained through various applications (EPRI, 2010; Marchmont Hill Consulting, 2012). Some of these have already reached commercial maturity, while others are visionary transformations of the industry.

This section describes the range of applications foreseen, and in many cases presently served, by UltraBattery[®] technology. The applications are linked with the required battery performance parameters, within the value proposition, which may be cross-referenced to the supporting tests.

5.1 Frequency Regulation

The fundamental task of an electric power system is to maintain the balance between electricity supply and demand at all times. This balance is exhibited in the system frequency, which is kept within quite tight limits around either 50 Hz or 60 Hz. The frequency is used as a control signal to maintain stable operation: if load increases or generation decreases, the frequency will fall until additional controllable generation compensates for the change.

Conversely, a decrease in load will allow an increase in speed of the generators that are spinning synchronously with the grid frequency, causing the frequency to rise. A number of generators are therefore assigned the role of 'frequency regulation', receiving a control

signal from the power system operator to increase or decrease their output so that the supply–demand balance and frequency are maintained.

In North America the power grid is divided into four main interconnectors (the Eastern, Western, Texas, and Quebec Interconnectors), and frequency is maintained on each of these and also between each of these through a complicated system of instructions from more than 100 ‘balancing authorities’ who direct energy flows throughout the North American grid.

This distributed approach is contrasted with the centralized, but still market-driven, approach on the world’s (geographically) longest grid: the National Electricity Market covering all the eastern states of Australia. On this grid the normal ‘dispatch’ of generators happens every five minutes according to a complex optimization algorithm generated by a central agency, the Australian Energy Market Operator (AEMO). The calculation minimizes cost according to bids from generation companies subject to the capacity of the transmission network between regions of generation and of demand. Remaining differences between supply and demand are corrected by frequency control ancillary services (FCAS).

Whatever control system is used, the goal is always to maintain the voltage and frequency of the grid at its rated levels. The difficulty for generators providing frequency regulation or FCAS is that this inhibits their ability to generate at full rated output and earn energy revenue. Also, the rapid response that is sometimes required is beyond the capability of some generators, depending on their ‘ramp rate’.

For example, many large coal-fired generators are most efficient when producing a steady output, and gas turbine and hydro generators are better suited to frequency regulation, although significant wear-and tear is caused by rapid ramping to follow the regulation control signal.

UltraBattery® technology is ideally suited to provide these frequency regulation services to the grid. It is suitable for pSoC operation which allows it to respond in both directions, by charging, discharging, or changing the rate of charging or discharging. It responds rapidly and can ramp much faster than any conventional generator, following the regulation control signal accurately, and providing a better service to the system operator. The public-domain test data that support this application are published in Ferreira et al. (2012) and Hund et al., 2008, and include test cycles representing regulation services.

An example of UltraBattery® technology performing grid-scale frequency regulation is Ecoult’s 3 MW installation within the Pennsylvania-New Jersey Interconnection (PJM) grid.

5.2 Smoothing and Ramp-Rate Control

Globally, the renewable energy industry has recognized grid integration as one of the key constraints on the continued growth of wind and solar PV energy as major players in the power industry. The problems lie both in the electrical characteristics of the wind and solar PV generators and in the intermittency of their energy production.

While it is possible to introduce technical measures to ensure that generators comply with network requirements, it is more difficult to deal with the inherent variability in the energy generation. This variability covers a broad range of time scales from seconds through hours to days and months. Interconnected energy systems, like those existing in the USA and in

the eastern states of Australia, manage variability using a variety of measures including normal dispatch practices, maintaining appropriate reserve capacity, renewable energy forecasting, frequency control ancillary services, and ramp-rate control.

On the Australian grid, AEMO has identified that the short-term (within one hour) variability in power-line flow can be quite substantial under some conditions where sizable wind generating facilities are present. This creates significant problems of voltage support and frequency control, as well as causing excessive peaking on transmission lines, thus reducing carrying capacity and increasing demand for high ramp-rate backup systems. This is particularly important where substantial renewable generation is present at the extremities of the grid or on relatively small capacity power lines, as is often the case for wind generation from high-quality resources that may be far from centers of demand. Ramp-rate control addresses short-term variability by controlling the rate of change of power output from a generator.

The integration of energy storage systems (at the point of generation or elsewhere on the transmission line) is an excellent method of ramp-rate management, because only a small energy storage capacity is required compared to the energy generated. Ramp-rate control is equally applicable to large-scale and small-scale renewable generation systems. Notably, one distribution utility in Australia has mandated energy storage for ramp-rate control of small-scale PV generators,

Standard lead-acid battery technology is unable to cope with the extreme cycling demands of ramp-rate control while delivering sufficient lifetimes. The UltraBattery[®] cell, in contrast, offers a much longer lifetime at high-rate pSoC operation while retaining the other advantages of lead-acid batteries including inexpensive construction and a high degree of recyclability.

Cycle profiles representing renewable energy smoothing applications for UltraBattery[®] cells are included in the public-domain test data reported in CSIRO (2012), Ferreira et al. (2012), Furukawa (2013), and Hund et al. (2008), as indicated in the Application Matrix on page 13.

Significant real-world data has now also been collected from a field installation in New Mexico. The Public Service Company of New Mexico (PNM) demonstration project installed an energy storage system into the grid comprising two elements: a 0.5 MW smoothing battery using UltraBattery[®] technology and a 0.25 MW/0.99 MWh peak shifting battery using advanced lead-acid batteries. The system was designed by Ecoult and both cell types were manufactured by East Penn Manufacturing (EPRI, 2012).

The project shows how energy shifting and smoothing on the grid can alter the profile of grid-scale renewables. UltraBattery[®] smoothing was applied to the output of a 500 kW solar PV array, where tests had measured ramp rates of 136 kW per second as solar energy was lost to cloud cover. Such large fluctuations in energy output become unsustainable as renewable penetration increases.

UltraBattery[®] technology has been shown to provide a viable and scalable solution. The provision by UltraBattery[®] cells of simultaneous shifting and smoothing (first shown to be viable during laboratory testing) has been very successfully demonstrated in this ongoing real-world project.

5.3 Power Quality

Electric power provided to customers should fulfill a range of power quality requirements for the benefit of both customers and the distribution networks that deliver the power. Keeping the voltage within the correct range is a primary safety requirement.

Other important elements of power quality include:

- + Harmonic content and phase balance, which govern the shape of the AC waveform
- + Power factor, which measures the relationship between voltage and current waveforms
- + Voltage sag duration and depth, which govern the permissible sub-second 'brownouts'
- + Interruption statistics, which measure the frequency and duration of the unavailability of power during each year.

Power quality is crucial to customers, particularly as appliances become increasingly sophisticated, and it is also critical for achieving safe and efficient transmission of power on distribution networks.

Customer needs have been changing due to the range of electronic appliances now found in typical residential and commercial buildings. Previously dominated by light bulbs, heating elements, and motors, customer appliances now include a variety of entertainment systems, computers, digital and plasma televisions, inverter-controlled air conditioners, and chargers for various personal electronic devices.

These new appliance types create customer demands for power quality that are often incompatible with the network code that specifies the performance requirements for distribution networks. Customers are also installing local generation systems, most notably rooftop solar PV panels, which further challenges the traditional role of distribution networks as deliverers of power from large-scale generation. Injecting power at points along the network, where solar PV systems are connected, dramatically changes the way voltage and protection (safety) should be managed by the network operator.

Battery energy storage systems are very good for managing power quality. Being connected to the grid via a power conversion system, they have the potential to manipulate the AC waveform in sophisticated ways that improve power quality measures, and the battery can provide real or reactive power to maintain voltage correctly. These functions can be performed for the customer, avoiding brownouts and blackouts, and to help manage the network.

Although any battery system can perform power quality functions in principle, such functions generally require the battery to be continuously in use, even at a low power level. UltraBattery[®] technology is particularly suited to this because it can sustain continuous operation at pSoC. Power quality functions can be performed by dual-purpose UltraBattery[®] systems that are primarily installed with another purpose in mind, which might be industrial/residential energy management or network peak shifting.

5.4 Spinning Reserve

Power systems have an inherent stability due to the inertia of powerful and heavy synchronous generators rotating at multiples of the grid frequency of 50 Hz or 60 Hz. The frequency is used as a control signal to maintain stable operation: if load increases or generation decreases, the frequency will fall until additional controllable generation compensates for the change.

Unexpected failures of generators or transmission lines will also cause the grid frequency to fall. Reserve generation capacity is managed over time scales from seconds to minutes to maintain the system frequency, and over hours to days to ensure that sufficient generation will always be available to meet load.

Reserve capacity for shorter time scales, which must be available when needed within minutes or even seconds, needs to be ‘spinning’ so that it is ready to ramp up rapidly. Any generator based on an engine consuming fuel will need some time to warm up from a cold start. Large, coal-fired generators typically require a day or more for a cold start, so their dispatch is carefully planned in advance, and if they are to provide reserve capacity they should be warmed up in advance and generating (spinning) at a low output level.

Gas turbines and gas or diesel reciprocating engines are more agile but still require a number of minutes for a cold start. Combined-cycle gas turbines are quite efficient, while open-cycle gas turbines are more agile but less efficient. It is unfortunately the case that quick-starting, agile generators are typically the least efficient generators, so that grid support services are often supplied using inefficient generation.

Moreover, while operating as spinning reserve, fuel-based generators will incur operating costs due to fuel consumption and wear and tear. Significantly, they also incur an opportunity cost of lost energy revenue while their output is held at level that is much lower than their nameplate capacity.

UltraBattery[®] technology is ideal for providing short-term ‘spinning’ reserve, because it can start instantly in either direction – charging (as a load) or discharging (as a generator) – without any warming up. It is able to sustain long periods of inactivity with a low rate of self-discharge and periods of continuously variable operation, depending on the system operator’s requirements, which in turn relate to the sources of variability in network load and generation.

UltraBattery[®] cells can also support longer-term spinning reserve by providing a fast-start capability to a fuel-based generator, providing instantaneous power and bridging the time taken for a cold start, after which the fuel-based generator would take over from the batteries. In effect, the UltraBattery[®] cell does the ‘spinning’ instead of the generator, with a consequent reduction in fuel consumption and wear and tear.

The Sandia National Laboratories have long understood the potential for batteries to serve multiple applications and have therefore developed compound cycle profiles for ‘stacked’ applications (Ferreira et al., 2012). By including periods of inactivity between periods of rapid response, these profiles effectively address the spinning reserve application, as marked in the Application Matrix on page 13. Data collected in real-world simultaneous smoothing and shifting (EPRI, 2012) also suggests that UltraBattery[®] technology is well suited to providing grid support services such as replacing fossil-based spinning reserve.

5.5 Residential Energy Management

Electricity is a significant household cost in both developed and developing economies. In nations with large, dispersed or remote populations increasing fuel costs, network investments, and other factors make interconnected networks expensive and difficult to maintain. In many regions – particularly remote locations and fast-growing urban areas in developing economies – energy security and reliability are significant concerns for households and businesses.

Residential electricity *production* is now quite normalized, and the electricity grid (designed to deliver energy from source to load) often now has to manage domestic loads that alternate between load and generator depending on the sun. This pattern requires grid operators to pay far more attention to demand management than was required under the traditional pattern of passive consumption, particularly as localized cloud cover could see available power drop with very steep ramp-rates in areas with high rooftop photovoltaic penetration.

The UltraBattery[®] presents an ideal technology for residential energy management services in such circumstances. It is designed for pSoC operation which allows it to charge or discharge at any time according to several application requirements, it is an effective energy-shifting battery for residential energy management according to tariff regimes and PV generation, and it has a high power capacity to offer network services in addition to residential services.

Ecoult is developing several modular systems designed for residential energy management, and a new testing program (Ferguson, 2013) has recently begun.

5.6 Energy Shifting and Demand Management

While many of the applications described here focus on flexible power import and export capabilities, the UltraBattery[®] is also an excellent energy-shifting device, and an installation can be sized so that energy-shifting requirements can be accommodated within a range of SoC and power capacity that ensure longevity.

High efficiency, measured on the AC side of the power conversion system, is required because loss of energy is undesirable in a shifting application while it may be tolerable in a high-power, low energy application. Public-domain test data using such profiles may be found in Ferreira et al., (2012), Furukawa, (2013), and Hund et al., (2008) as indicated in the Application Matrix on page 13.

Energy shifting is a part of the requirement for residential energy management and multipurpose use in datacenters and commercial buildings. These demand-side applications are complemented by several opportunities for energy storage to improve the safety and efficiency of electricity networks.

The electricity market and system operator together ensure that the totals of supply and demand are matched within the balancing region. As the transport mechanism, networks are responsible for linking points of supply and demand and managing local peaks and troughs and differences that may occur on a smaller scale. The network can always be built with enough capacity to do this, but there is an important question of investment efficiency, and

networks are very expensive investments, typically accounting for as much as half of the cost of electricity.

For example, in Western Australia the average load is approximately half the maximum load, and the load exceeds 90% of the maximum load for less than 0.5% of the year. Other global regions report similar figures, showing that the last 10–20% of network capacity is grossly underused and therefore represents an inefficient investment. Energy-shifting capability is an alternative investment that can reduce peak demands by spreading the same energy consumption over a longer period.

Peak demand management by energy shifting can happen in a variety of circumstances on the network. Growth of peak demand has been a longstanding phenomenon globally, particularly due to increasing use of air conditioning, increasing house sizes with an increasing range of appliances, and population growth. Typically a network element, such as a transmission line or a transformer, is marked for replacement according to regular reviews of network condition and capacity. However, this investment must always compete with many others and, due to the size of overall network investment, there are formal processes to consider alternatives that may be more efficient.

Energy storage for shifting consumption is an attractive alternative because it can also perform many other useful network functions, such as injecting real or reactive power as necessary to maintain voltage in the correct range for customers, helping customer loads to ride through network faults, and in some cases allowing islanded operation sustained by local renewable energy generation. Each of these functions can improve the level of service and remove the need for additional equipment.

Most distribution networks use three-phase components and transmission lines and carry multi-MW of load. They require substantial energy storage facilities to allow a useful level of demand management. Opportunities for small-scale storage can also be found, though, in the many single-wire earth-return (SWER) networks that serve smaller communities in rural areas. These networks are often operated close to load limits, with aging infrastructure, and long line lengths per customer. Frequently they pass through sensitive landscapes including fire-prone and difficult-to-access areas, and this can create a good case for removing the SWER line and installing a remote-area power supply (RAPS) (another application for energy storage, discussed below).

Alternatively, energy storage can help to extend the network's lifetime and defer a major investment in either in feeder upgrade or a RAPS that would allow the feeder to be decommissioned.

5.7 Diesel Efficiencies

Geographical constraints often prevent interconnection between power systems, and RAPS are installed to provide electricity to islands and remote communities. These are alternatively known as microgrids and are generally either fossil-fuel powered or, increasingly, powered by a hybrid system employing renewables with a fossil fuel backup. The economic case for using renewable generation to reduce fuel costs in remote power systems is strong in many such situations, particularly as diesel fuel costs increase. Energy storage provides the mechanism by which this can be achieved while maintaining or improving the reliability of the power supply.

Smaller communities and individual homes or farms can use ‘standalone’ RAPS in which the diesel genset is relegated to providing backup power. The renewable energy generator provides most of the energy required by the load, and charges an energy storage system that has a large capacity compared to the daily energy consumption. A diesel genset is used as a backup when there has been insufficient renewable energy for some time or when the load is particularly high due to an unusual activity, such as arc welding. Fuel efficiency is achieved due to the diesel genset being able to remain off for most of the time.

Larger communities require ‘hybrid RAPS’, in which one or more diesel gensets are usually operating and supplementing the renewable energy generator. The energy storage system helps to balance this total supply against the load demand; this requires a relatively small energy capacity.

Energy storage is used to absorb rapid changes in both renewable energy output and system demand, so the diesel gensets are exposed only to a slowly changing operating regime. With storage in place the diesel genset does not need to operate at low load (that is, as spinning reserve), since the storage can cover moments when the renewable energy output drops suddenly. Fuel consumption of a diesel engine increases considerably the further below its rated capacity it is required to perform, and efficiency is approximately 23% less when operating at 25% of the rated load than it is operating at rated load. This is an important factor in deciding the desirable minimum loading of the diesel genset.

Another crucial factor is that sustained operation under light-load conditions significantly increases the risk of engine failure, and can cause premature aging of the diesel genset. Operation at light load also reduces the response time of the genset. Thus, diesel gensets are normally set to operate toward the rated load and, at the lowest, in the range of 30–50% of rated load.

Using energy storage, therefore, directly improves diesel operating efficiency because higher loadings can be achieved for longer periods, and also improves diesel engine longevity. The UltraBattery[®] has good responsiveness and efficiency at pSoC, which makes it an excellent technology for balancing hybrid RAPS, in the same way as it can provide spinning reserve for interconnected power systems. The UltraBattery[®] cell is also a highly capable deep-discharge energy store for standalone RAPS in which it might be required to supply the load for prolonged periods.

5.8 Multipurpose use in Datacenters and Commercial Buildings

Datacenters are very large electricity users and they typically have an existing energy storage resource in the form of a battery backup system. These storage systems are already grid-connected and present an opportunity to provide services to the grid including regulation services and demand management, as discussed in previous sections, provided that the batteries are capable of delivering these services in addition to backup power. Traditional lead-acid batteries cannot sustain continuous charging and discharging operations without dramatically shortening their lifetime: rather, they are designed to sit on ‘float current’ fully charged and waiting for a UPS event. UltraBattery[®] storage units are fully compatible with traditional UPS batteries in a datacenter, and they can operate in continuous charge and discharge to provide grid services.

The provision of grid ancillary services offers a new source of revenue for what is today a ‘cost only’ investment for datacenter operators. The widespread presence of backup energy in datacenters today presents a substantial buffer for the grid, and an enormously valuable, already existing resource that can be unlocked to support variability management and accelerated renewable integration.

Moreover, carbon dioxide savings extracted from using energy storage instead of fossil fuelled generators for frequency regulations may count toward a datacenter’s contribution to carbon dioxide savings in markets with carbon pricing mechanisms. Additionally, this model offers a very compelling advantage of economic returns: revenues from the provision of frequency regulation services in parts of the USA exceed the marginal cost of investment from using a slightly bigger store of UltraBattery® cells to fully support the dual purposing of a datacenter.

Datacenters are an example of a wider variety of commercial buildings that could find multipurpose UltraBattery® energy storage an attractive facility. As well as providing a UPS and ancillary services to the grid, UltraBattery® systems can help manage energy flows within a building, which may include peak demand reduction to reduce capacity charges, consumption or market dispatch of locally generated energy from rooftop PV arrays, and energy shifting to minimize energy costs according to a fixed or variable tariff regime.

This multipurpose application is a combination of demand management and frequency regulation and, as such, the same public-domain test data may be taken to support it (Ferreira et al., 2012; Furukawa, 2013; and Hund et al., 2008).

5.9 Micro- and Medium HEVs

In part due to tighter regulation of vehicle emissions, HEVs are now a mainstream alternative to vehicles powered only by an internal combustion engine, with most major car manufacturers offering a range of HEV options in parallel to their traditional range, including some commercial vehicles. Micro-, medium, and full HEVs are varieties with different requirements with respect to battery size and capability, and all may be well served by the UltraBattery®.

Micro-HEVs have an ‘idling-stop’ function that stops the internal combustion engine when the vehicle stops. They also use regenerative braking to recover some of the vehicle’s energy of motion to help charge the battery. With these innovations the fuel efficiency is typically increased by approximately 10% compared to a non-hybrid vehicle. Micro-HEVs do not provide electric drive to the wheels of the car. They use a single 12 V battery in a similar format to a traditional car battery; however, the demands on the battery are significantly different.

In micro-HEVs, power is not available from the alternator when the engine stops idling, so electrical appliances such as lights, audio systems, and air conditioning must be powered from batteries, resulting in a deeper discharge. To accept charge from regenerative braking efficiently, the battery is kept at pSoC, typically about 90% full, and it must be able to withstand high charging rates.

This contrasts with non-hybrid vehicles, in which the battery floats on full charge using the alternator to provide mild charging rates. Micro-HEVs usually need to restart the engine

when the driver releases the brake pedal after stopping, so the number of large-current discharges increases compared to non-hybrid vehicles. (Some micro-HEVs use combustion to restart the engine by sensing the cylinder positions.) These factors mean that a normal car battery would have a very short lifetime, so special battery technologies are required.

Medium (or mild) HEVs provide electric propulsion. They use idling-stop and regenerative braking, as do micro-HEVs, with the additional requirement of acceleration. This moderates the power demands on the internal combustion engine and typically increases the fuel efficiency by approximately 20–25% compared to a non-hybrid vehicle. They include the same innovations as a micro-HEV and the electric motor, alternator and battery are larger and play a greater role in the operation of the vehicle. For greater efficiency for sustained high-power discharge during acceleration, 144 V battery packs are used rather than single sealed or flooded units.

A full HEV is similar to a medium HEV except that the electrical components are much larger in size, and able to propel the vehicle under electric power alone, while the internal combustion engine is consequently smaller. Usually the battery pack voltage will exceed 200 V. A more sophisticated control system is needed to optimize efficiency under a range of operating conditions, increasing the fuel efficiency by approximately 40–45% compared to a non-hybrid vehicle in an urban setting.

All the advantages of HEVs apply to commercial vehicles as well as private cars, and there are additional factors that make them particularly attractive.

- + Commercial vehicle fleets are centrally managed from purchase to disposal, so there is a well-informed framework within which to evaluate the economic and environmental benefits of switching to HEVs.
- + Commercial vehicles tend to have a constant pattern of use, which also helps to quantify the benefits of switching to HEVs, and may support the introduction of fully electric vehicles – there is no need to allow for an occasional long-distance journey that may exceed the range provided by the battery pack.
- + The pattern of use typically includes regular intervals at a depot or way station, where charging may occur.
- + Finally, most commercial fleet vehicles operate in urban environments with frequent stopping and starting and a heightened sensitivity to vehicle emissions and noise.

For all of these reasons, the benefits of HEVs and fully electric vehicles are likely to be maximized in the case of commercial vehicles.

Several public-domain UltraBattery[®] test programs have targeted HEV applications; these are indicated in the Application Matrix on page 13.

5.10 Railways

Electric power is widely used in railways, and battery energy storage can be used to provide hybrid power with similar benefits to those obtained for road vehicles. The transition to hybrid power should be easier because many trains already have both diesel and electric motors. In Europe, for example, just over half of the train tracks are electrified, and some trains are

designed to operate with diesel or electric drive. Energy storage can also provide important support to the stationary electricity infrastructure that supplies overhead or third-rail power to trains.

Hybrid power technology has so far been limited mostly to shunting locomotives, which have particularly high energy losses due to continuous start–stop operation. Long investment planning cycles, an intense focus on reliability, and the more extreme conditions faced by trains have inhibited change. Nevertheless, the first hybrid passenger trains are now starting to appear on routes with frequent stops that have many opportunities to recharge batteries using regenerated braking power.

There are several advantages to this beyond efficiency. Hybrid power allows emissions-free train movements in sensitive or populated areas, particularly around stations where acceleration occurs. Trains have a lower power-to-weight ratio than road vehicles so they are less sensitive to the additional weight of a battery system. Railway rolling stock is also built to last a long time, so it can make good economic sense to retrofit a hybrid power system to an existing locomotive or passenger set, rather than waiting to order replacement rolling stock.

Electric railways require an electricity distribution network that operates in parallel with the grid that supplies the rest of the community, having only high-voltage substations in common. The two grids cannot be too closely tied due to the detrimental effects that passing trains may have on the quality of power delivered to urban or rural electricity customers. Particularly near railway stations and on inclines, the load is characterized by peak demands of great intensity separated by significant periods of low load.

As for the general power grid, supplying very ‘peaky’ loads requires a strong but underutilized network, which tends to be a highly inefficient investment. Stationary energy storage at strategic points along the railway can supply peak demands of passing trains while being charged in a more continuous fashion by a lighter, and much cheaper, electricity distribution network. This application requires a good energy-shifting battery that has high power output capability.

The application of battery energy storage to railways is sufficiently different from other HEV (motive) and network support (stationary) applications that there are no public-domain test data presently available to demonstrate the effectiveness of UltraBattery[®] technology in this role. However, extrapolating from existing results, it is very unlikely that UltraBattery[®] technology would not be suitable for application to energy storage along rail corridors.

6 Conclusion and Further Research Opportunities

A wide range of tests has demonstrated that the UltraBattery[®] is a highly capable and long-lasting multipurpose energy storage technology. These tests have been performed by government laboratories and through collaborations between several organizations. Much of the data is available in the public domain. This White Paper has assembled some of the significant publicly available test data in support of the key benefits of the UltraBattery[®] technology: in particular, long life, high efficiency, few refresh cycles, high charge acceptance, and cell voltage stability.

The market segments where these key benefits are important have been described through 10 areas of application. They include grid and automotive applications, some of them mature and already attracting energy storage solutions, others emerging and ready for commercial demonstration using capable technologies. These applications are also linked to the test data, and the UltraBattery[®] is shown to be well suited to them all.

This White Paper recommends that, while ongoing test regimes will continue to provide deeper understanding of the technology, newly available field results from commercial operations should now begin to be aggregated to allow a more nuanced understanding of how UltraBattery[®] technology performs in a wide range of operational conditions. As large amounts of data become available from kW and MW scale implementations, the technology's performance parameters can be understood under various environmental conditions and charge–discharge regimes, and this will likely expand the range of potential applications available to this important and valuable storage technology.

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