

THE EVOLUTION OF ULTRABATTERY® TECHNOLOGY: FROM INNOVATION TO LONG-LIFE, GRID SCALE ENERGY STORAGE DEVICE

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ABSTRACT

It has long been considered necessary that large-scale energy storage be installed on power grids in developed and developing economies. Storage dampens the grid system, reduces its inefficiencies, offsets peaks, reduces fossil fuel loads and creates the opportunity for larger penetration of renewable energy into the grid. However there have been substantial technical, safety, environmental and financial hurdles to the realization of true grid-scale storage and no single technology has been able to present a safe, environmentally palatable solution to suit projects at various scales. The development of a hybrid supercapacitor and lead acid cell – the UltraBattery® – ten years ago showed that lead acid cells had very much more significant potential than was previously believed possible. When experimental results showed that the cell was further capable of grid-scale smoothing and ancillary support the economics of grid storage suddenly began to shift. This paper explains how a technology envisaged for hybrid electric vehicle use has blossomed into a storage solution with proven multi-MW credentials in grids around the world and describes how mass grid storage may begin to be installed on the kW by kW scale as the market is opened for small to medium enterprises and forward-thinking utilities to install dual purpose backup schemes with the potential to earn revenues in the multi-billion dollar smoothing, shifting, energy retail and grid regulation markets.

Keywords: *Ultrabattery, advanced lead-acid battery, variability management, energy storage, solar smoothing and shifting, wind smoothing and shifting, diesel efficiencies, dual purpose energy storage*

INTRODUCTION

This paper examines the development of UltraBattery® technology and explains technological enhancements and discoveries made during laboratory testing and field installations from the time of its invention in 2003 through to 2013. A review of experimental results and an overview of present installations is given, and future uses of the technology are discussed.

It is ten years since UltraBattery® technology was invented and during that decade multiple research programs have published results showing the exceptional performance of UltraBattery® technology over conventional lead acid cells and competing chemistries. The technology is presently installed in several commercial / demonstration projects performing renewable smoothing, grid ancillary support and hybrid electric vehicle power. Various results from these projects are discussed below.

A significant future use of the technology is expected to be in multiple-use applications, whereby banks of UltraBattery® cells are used to support the grid while the grid is available and to switch to providing UPS support when the grid is not available. This type of application requires high rate partial state of charge cycles to be performed simultaneously with energy shifting

operations, in a cell that is consistently prepared to provide backup functionality in the event of a grid failure. Experimental results suggest UltraBattery® can perform admirably in multiple-use applications and field trials have confirmed that the technology is well suited to this dual role.

TECHNOLOGY BACKGROUND

During the past ten years UltraBattery® technology has developed from concept to a commercially tested product on the verge of mass production. The decade in question has coincided with a period of increasing recognition that electric power grids can operate more effectively and tolerate higher penetration of renewable generation when energy storage is incorporated into their infrastructure. The decade has also seen rapid growth and maturity in the hybrid electric vehicle (HEV) market

UltraBattery® technology was invented in 2003 by researchers led by Dr Lan Lam at Australia's national science agency, the Commonwealth Scientific and Industrial Research Organisation (CSIRO). Developed during research into high power batteries for HEV use, the project objective was to produce a battery that had the cost, safety and environmental credentials of valve regulated lead acid (VRLA) batteries combined with the

charge/discharge rates and performance characteristics of newer chemistries (e.g. supercapacitors, NiMH cells, and lithium cells) more typically envisaged as the likely energy-store for HEVs. The crucial issue of cost-of-storage is a complicated function of minimized initial production cost, cell longevity, efficiency and up-time and UltraBattery[®] has been shown to excel in all these areas.

A key technological breakthrough came when the CSIRO research team recognized that for HEV use the most significant limitations of VRLAs (lower rate of charge acceptance compared to competing chemistries, shortened lifespan in partial state of charge (pSoC) applications and high levels of negative electrode sulfation) could all be *simultaneously* overcome if the battery cell was modified so that it contained an ultracapacitor (alternatively called an asymmetric supercapacitor) in parallel with the existing battery chemistry.

It was hypothesized that both the lead acid cell and ultracapacitor could utilize the existing VRLA positive electrode and the existing VRLA electrolyte (aqueous H₂SO₄) in their charge/discharge chemistries. This hypothesis proved correct, leading the way to the development of an ultracapacitor-enhanced lead acid cell (an “ultra”-battery) that could use existing standardized lead acid cell packaging and be produced using existing, albeit modified, lead-acid manufacturing facilities.

In the development of UltraBattery[®] the negative electrode was subjected to significant adaptation so that alongside the standard sponge-lead negative plate of the VRLA cell a specially prepared carbon electrode was inserted and electrically connected to the sponge lead electrode. The dual negative electrodes were sized such that the very high charge acceptance of the ultracapacitor and the large energy storage capability of the lead acid cell were both maximized.

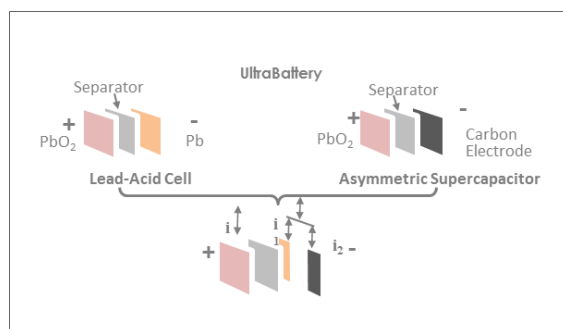


Figure 1: Schematics of standard lead acid cell (top left), supercapacitor (top right) and their combination in the UltraBattery[®] cell (bottom)

The presence of the carbon negative electrode was found to alter the nature of the chemical reaction taking

place at the negative electrode so that continuous partial state of charge (pSoC) operation was possible without damaging levels of sulfation occurring on the lead electrode.

Once the cell was prototyped and testing began, it was quickly realized that the possible applications for UltraBattery[®] technology were far broader than the HEV usage originally envisaged. Various stationary battery applications, including renewable smoothing, grid ancillary support and support for energy backup systems (e.g. UPS) were considered possible for UltraBattery[®] technology, and various testing regimes were embarked upon at private and government laboratories.

Tests soon began to confirm that UltraBattery[®] cells had significant performance advantages over both standard VRLA batteries and competing chemistries. Furthermore the cost benefits of UltraBattery[®] technology became apparent when it was recognized that the lifetime of the cells (under various test conditions) could be anything from twice, to orders of magnitude higher than that of existing VRLA cells, whereas the cost of production was reasonably low and (with mass production) not likely to be significantly higher than standard VRLA cells.

Over the next decade modifications were made to the UltraBattery[®] cell in response to test results and the technology has developed from prototype to the major component in a robust and field-tested storage solution with facilities ready for large-scale production. (The “storage solution” refers to any of the various packages developed by Ecoult, consisting of UltraBattery[®] cells, installation and testing techniques and battery management and monitoring software).

Significant improvements in UltraBattery[®] performance over the decade of testing have made it possible to envisage (and subsequently prove both experimentally and in grid-connected field installations) that UltraBattery[®] technology had the potential for “dual use” applications. That is, whereas most rechargeable batteries are designed for either “power” applications (high rate of discharge followed by a slower charge back to full capacity) or for “energy” applications (slower, sustained energy release over longer time periods followed by slow charge back to full capacity), UltraBattery[®] technology was found to be well suited to providing both of these and, remarkably, to providing them simultaneously.

Importantly the technology was found to run for long periods (hundreds, thousands and, for some applications, millions of cycles) without the need to bring the cells back to full capacity for a “refresh” cycle, whereas traditional VRLA cells require frequent refresh cycles to prevent failure due to sulfation.

RESEARCH AND TESTING REVIEW

There are broadly three types of test results available for UltraBattery[®] technology.

Firstly, many publicly funded or partially publicly funded laboratories (including, among others, CSIRO, Sandia National Laboratory (SNL), Idaho National Laboratory (INL) and The Advanced Lead Acid Battery Corporation (ALABC)) have performed experiments on UltraBattery[®]. The methodologies and results of these publicly funded tests are published and are generally available online (and some are discussed below).

Secondly, UltraBattery[®] technology has been successfully implemented in HEVs and in several MW-scale energy storage projects globally, delivering ancillary services, wind and solar smoothing and energy shifting. Many field results and system outputs are publicly available, showing the ability of UltraBattery[®] technology to a) power HEVs, b) deliver grid ancillary services very efficiently and c) successfully manage fluctuations and ramp rates of renewable sources to create highly dispatchable output to wider power grid.

Thirdly, confidential tests have been carried out in the course of the development of the technology. Some of the publicly available results from these tests are presented below.

The three key areas reported on by the research have been a) performance in partial state of charge (pSoC), b) rate of charge acceptance and c) longevity under various working conditions.

Most lead acid batteries have reasonably long life spans if they are regularly refreshed and properly recharged; however they generally quickly deteriorate under pSoC use (a regime that is generally outside of their design parameters).

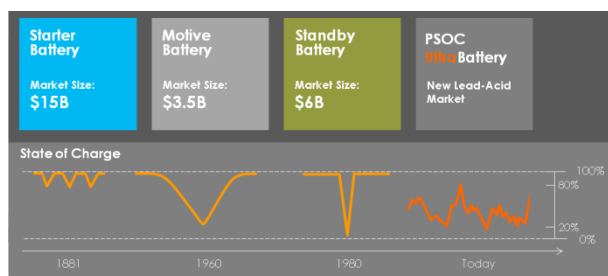


Figure 2: History of lead acid battery technology

Figure 2 shows the charge/discharge characteristics of the UltraBattery[®] cell (at right) compared with those of traditional lead acid technology. In early lead acid cells high power was available for brief periods, depth of discharge needed to be very low and refresh to full capacity needed to be performed frequently. Later enhancements allowed deep discharge to be performed

at increasing rates of charge and discharge, but constant refresh cycles (back to full charge) were still required.

Unlike previous lead acid types UltraBattery[®] cells can sustain prolonged operation in the pSoC range. This range is indicated schematically in the right hand trace in Figure 2. Lead acid cells are generally highly efficient to charge (above 90% efficient) in the middle region of charge, but inefficient (below 60% efficient) toward the top of charge range [1]. UltraBattery[®] cells can therefore operate very efficiently as they rarely needed to leave the middle of charge range, and perform well in continuous pSoC use. Research (e.g. [3], [4]) has indicated that the cells also endure long periods between refresh cycles, have long overall lifetimes and exhibit few of the typical lead-acid failure modes.

Early results came from bench testing by CSIRO and Furukawa Battery in Japan and were published in 2007 by UltraBattery[®] inventor Dr Lan Lam. These results confirmed that the first generation of the UltraBattery[®] cell had as much as four times the lifespan of traditional VRLA cells in pSoC applications and moreover was able to provide and absorb charge rapidly enough to simulate the rates required during HEV vehicle acceleration, meeting or exceeding the requirements for power, available energy, cold cranking and self-discharge for HEV use. Most encouragingly, the performance of the early UltraBattery[®] cells was proven to be comparable with that of the more expensive Ni-MH cells (tested concurrently) [2].

Such results raised expectations that UltraBattery[®] could perform well in grid and renewable smoothing applications. An independent study published in 2008 at Sandia National Laboratories and funded by the US Department of Energy was devised to test the UltraBattery[®] cell under a high-rate-partial-state-of-charge (HRPSOC) cycle profile designed to simulate the ancillary regulation services of a utility and a wind farm energy smoothing application [3].

In this test UltraBattery[®] was compared against a standard VRLA battery. The standard VRLA was tested using a 1C rate of discharge (i.e. full capacity is discharged in one hour at the 1C rate). For the UltraBattery[®] tests comprised groups of 100 or 1,000 rapid charge-discharge cycles at a 1C, 2C, or 4C rate, covering a range of 10% depth of discharge (DOD. (4C represents a high rate cycle, and would discharge the cell's full capacity in 15 minutes).

During testing the traditional VRLA battery dropped below 80% of initial capacity after 1,100 cycles. UltraBattery[®] lasted about thirteen times longer, exceeding 15,000 cycles (Figure 3). The UltraBattery[®] cell was also able to withstand more than ten times the number of rapid cycles as compared to the VRLA battery (1,000 vs. 100) and maintained a lower cell temperature

even at the 4C rate than experienced in the standard VRLA cell at the slower 1C rate [3].

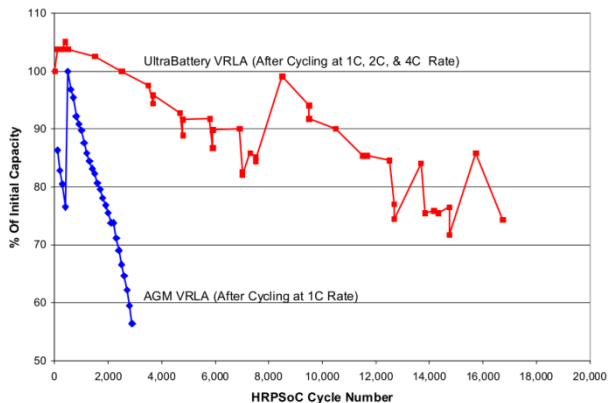


Figure 3: UltraBattery® and VRLA Battery 1C₁ capacity after high rate pSoC testing

Field testing in 2008 (by UltraBattery® manufacturer Furukawa Battery Co Ltd.) in a Honda Insight HEV followed [4]. These internal results showed conclusively that UltraBattery® technology could meet the demanding requirements of HEV applications, where continuous and rapid charge and discharge cycles were required to store and release the very large amounts of energy involved in assisting acceleration and braking of a passenger vehicle.

The Furukawa tests in 2008 were quite revolutionary in that they indicated that the UltraBattery® cells could tolerate extremely long periods – over 100,000 miles of driving – without a refresh charge and without suffering significant degradation. Indeed the most intriguing results from the Furukawa research were around the longevity of the cell. A reasonably aggressive target “lifespan” of 200,000 cycles had been set as the goal for the UltraBattery® cell. However it was found that the cell exceeded this sevenfold, achieving 1.4 M cycles by the end of the test [4].

This 2008 research also included a study of UltraBattery® technology being used as a smoothing mechanism for renewable power generation. Initial results suggested that the UltraBattery® had a lifespan around 1.5 times that of VRLA cells in renewable smoothing applications. (This result should be compared with results from Sandia National Laboratories, four years later in 2012, discussed below and referred to in Figure 4.)

A peer reviewed paper by Furakawa, Lam and Monma [5] in 2010 confirmed the 2008 results. It concluded that the UltraBattery® had at least four times the lifespan of traditional lead acid cells and again confirmed it had cycling performance comparable with or better than the more expensive NiMH cells. Importantly, this research concluded with a disassembly of the test cells and this

process revealed that the conventional VRLA under the same test conditions had failed (as expected) due to sulfation of the negative electrode whereas (as hypothesized) there was scarce evidence of sulfation at the negative electrode of the UltraBattery® cells.

In 2012 research at Sandia National Laboratories (SNL) looked more closely at UltraBattery® technology being used in a utility setting. The 2012 SNL test profile for high-rate, partial state-of-charge (pSoC) cycling represented a utility application and has drawn substantial positive attention to the UltraBattery®. UltraBattery® cells constructed by East Penn Manufacturing ran for more than 20,000 cycles maintaining very close to 100% of their initial capacity, as shown in Figure 4. By comparison the conventional VRLA battery fell below 80% of its initial capacity after around 2,500 cycles.

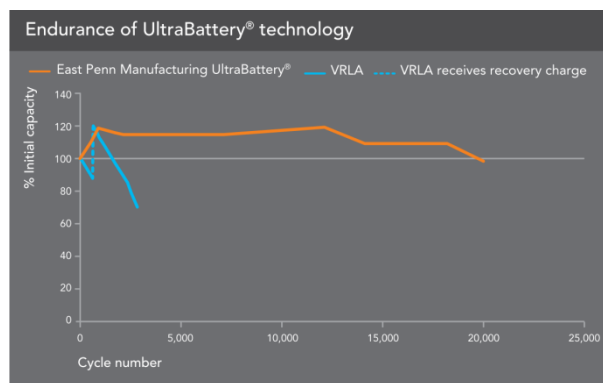


Figure 4: Comparison of capacity retention between UltraBattery® and VRLA in high rate partial state of charge testing. The UltraBattery® cell was cycling at 5% DOD, the VRLA at 10% DOD.

(Graph recreated from SNL’s 2012 report [6])

DEVELOPMENTS IN ULTRABATTERY® TECHNOLOGY IN REPONSE TO TESTING

The findings of independent and internal testing allowed Ecoult and its parent company (US battery maker East Penn Manufacturing) to experiment with various aspects of UltraBattery® technology to develop chemistry, hardware, installation and software techniques to suit various stationary storage applications. (A partner company, Furukawa Battery Ltd of Japan, holds a license to develop HEV and EV solutions.) Key improvements were made by varying the dimensions and manufacturing techniques of the negative plate electrodes. In order to maximize the capacitive characteristics of the cell while minimizing its tendency to suffer sulfation in high rate pSoC operation an optimal balance between lead and carbon electrodes has been determined. The result of this and various other developments (in chemistry and in software) has been very significant increases in cell longevity (Figure 5).

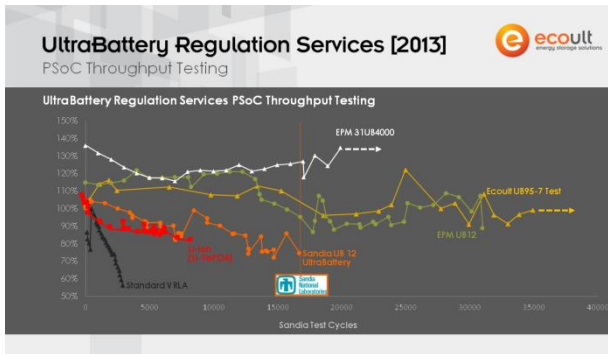


Figure 5: SNL testing of VRLA, Li-Ion and UltraBattery® technology (bottom three traces) is compared with the most recent 2013 internal testing (top three traces). Significant longevity increases have been achieved.

Furthermore there has been significant internal investigation and research into the optimal cell size for various applications. Where the original UltraBattery® was conceived in the format of large industrial 2 V cells, there were significant benefits to developing multi-cell (12 V) versions of UltraBattery® technology (Figure 6).

UltraBattery Formats



Figure 6: Various 12 V (top row) and 2 V (bottom) formats have been developed to suit a range of stationary applications

The 12 V cells create new challenges for battery monitoring since the initial algorithms, hardware and software for UltraBattery® were developed to manage each cell individually, whereas a 12 V cell only allows the software to “see” six cells as a block. Algorithms needed to be developed to monitor cell state of charge, state of health, throughput and temperature of groups of six cells.

However the significant advantage of extending UltraBattery® from 2 V to various 12 V formats is the creation of opportunities to install storage on scales from large generating plant right down to single domestic installations. Ecoul is pioneering the modularization of energy storage so that storage consistently moves closer to a plug-and-play solution that might be easily

distributed on the grid. A small solar installer or a large industrial firm should soon both be able choose from off-the-shelf storage solutions with known characteristics and dependable battery management and monitoring software.



Figure 7: Three UltraBattery® energy storage options. The cabinets at left and centre suit domestic and SME installations and contain 12 V units. The right hand racks contain 2 V UltraBattery® cells and might be found in MW scale grid support applications.

SELECTED CURRENT PROJECTS

UltraBattery® installations in the US and Australia currently cover renewable shifting and smoothing, grid support services, and microgrid support. Figure 8 shows a number of these installations and various results have been made publicly available from them.

A large UltraBattery® grid installation in the PJM interconnection in the US sells 3 MW of frequency regulation in to the system and provides demand management services to a local utility (Met-Ed, a FirstEnergy Company) during peak periods. The cells see multi-MW swings on a minute by minute basis and the full capacity of the cells is cycled many times daily as it responds to the demanding signal from the grid with sub-second accuracy.



Figure 8: Six current projects show the range of MW scale applications suited to UltraBattery® technology

The US Electric Power Research Institute (EPRI) has recently reported on a Public Service Company of New Mexico (PNM) project in which a 0.75 MW-scale storage

solution (utilizing UltraBattery® technology) was installed to provide grid stabilization and renewable smoothing for a 500 kW solar farm in New Mexico. The project has demonstrated that renewable smoothing and shifting is a valuable addition to the solar project, allowing it to provide variable levels of smoothing with algorithmic control and to shift peak midday solar energy to meet afternoon demand.

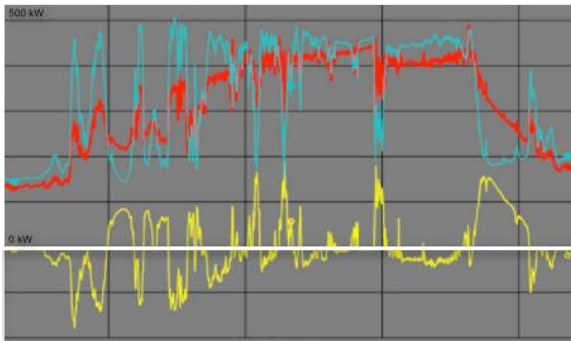


Figure 9: PNM New Mexico – UltraBattery® smoothing to achieve ramp rates acceptable to the grid operator showing solar meter (blue), cell charge/discharge above and below 0 kW (yellow) and system output to the grid (red). The vertical lines are approximately at half hour intervals (adapted from [8])

FUTURE PLANS

UltraBattery® has a significant role to play as grid operators, governments and markets wake up to the growing need for grid scale energy storage. The technology continues to improve: our research focus is shared between software design, low-power cooling systems, string management, reducing the already very low cell impedance and improving cell longevity. However UltraBattery® is a now a mature technology with significant experimental and real-world evidence of its energy storage abilities.

The real changes required now are to market models that are currently under-prepared for energy storage gaining a larger profile in power grids. The need and the potential returns are very real. Recent research by Navigant estimates that globally in 2013, 17,238 GWh of potential renewable energy will be curtailed because it is not generated to coincide with periods of sufficient demand. By 2023 Navigant projects this curtailment to reach 567,053 GWh of output. Navigant has valued the 2023 curtailed renewable production at \$US30 billion. By comparison the investment required to capture that energy in storage is estimated to be around \$US10 billion [7].

The market for renewable smoothing and shifting is one of several multi-billion dollar energy storage markets; microgrid support (in remote communities and mine sites) and grid ancillary support are two more. Germany and California have recently mandated energy storage within their power grids and the US Federal Energy

Regulatory Commission (FERC) has passed recent rulings to ensure that speed and accuracy (the domain of electronically controlled battery-based storage) are criteria for higher reward in the ancillary support market.

But there is limited appetite for single operators developing and investing in energy storage on the GW scale. Rather, Ecoult sees a future power grid that has relatively small numbers of very large scale storage installations and very large numbers of smaller distributed storage installations. A grid that can expand and contract is not nearly so prone to cascading failures (as witnessed daily in developing economies and infrequently, albeit catastrophically, in developed technological economies). The safety aspects of UltraBattery® technology make it perfectly suited to distributed installation in homes and businesses (and cars, based on advances being made by Furukawa Battery of Japan.)

However, to help create market conditions to make energy storage attractive to large and small business, Ecoult and UltraBattery® are developing strategic partnerships with electricity market players through which innovative arrangements would allow their consumers to purchase or lease UltraBattery® energy storage to cover critical outages while earning revenues from selling into the ancillary services and energy market. The most likely early adopters are data centers, already committed to energy storage, usually in the form of lead-acid based UPS systems, but overwhelmingly interested in a revenue-based UPS system based instead on UltraBattery® technology, which has the same voltage and installation characteristics as existing UPS batteries and would simply plug in to existing infrastructure. A recent Forbes Magazine article described Ecoult's dual-purpose UPS model as "clever business planning" that could see data centers become the grid's "best friend". [9]

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BIOGRAPHICAL NOTE

John Wood is the Chief Executive Officer of Ecoult. He joined the energy storage community in 2008 having previously launched technologies globally in security, identity, payment technology, and telecommunications.

As a technology CEO for more than 20 years, John has had the good fortune to have worked with excellent individuals and led outstanding teams that have created businesses and numerous successful products and solutions from the ground up that are used and trusted by many of the world's largest enterprises and governments – either directly or under license by many of the largest global technology enterprises.

John is now leading the Ecoult effort to commercialize the UltraBattery® storage solutions.